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Single-use supermarket food packaging and its alternatives:

Recommendations from Life Cycle Assessments

Acknowledgements

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Table of contents

Image: Assorted apple packages in a supermarket refrigerator.(ALEAIMAGE, iStockphoto.com)

List of figures

List of tables

Abbreviations

ADP	Abiotic Resource Depletion Potential
ATB	Air-through bonded
B2B	Business-to-business
B2C	Business-to-consumer
GHG	Greenhouse gas
GWP	Global warming potential
Hi O_2 MAP	High oxygen modified atmosphere packaging
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LPB	Liquid packaging board
LUC	Land use change
MAP	Modified Atmosphere Packaging
ODP	Ozone layer depletion potential
OECD	Organisation for Economic Co-operation and Development
OLB	Opaque Laminating Base
PREI	Packaging Relative Environmental Impact
RPC	Reusable Plastic Crate
PUL	Polyurethane laminated fabric
TAC	Technical Advisory Committee
UNEP	United Nations Environment Programme

Types of plastic

APET	Amorphous polyethylene terephthalate
BBP	Bio-based polyester
EPS	Expanded polystyrene
EVA	Ethylene vinyl acetate
EVOH	Ethylene vinyl alcohol
GPPS	General purpose polystyrene
HIPS	High Impact Polystyrene
LDPE	Low density polyethylene
OPET	Oriented polyethylene terephthalate
OPP	Oriented polypropylene
PA	Polyamide
PE	Polyethylene
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoate
PLA	Polylactic acid
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
rPET	Recycled polyethylene terephthalate
TSH	Thermoplastic starch
XPS	Extruded polystyrene
XrPET	Gas barrier recycled polyethylene terephthalate

Image: White yogurt packages on a production line in a dairy processing plant.(Cylonphoto iStockphoto.com)

Executive summary

Single-use plastic packaging is abundant in supermarkets and retail stores, where it cheaply and effectively fulfils the important functions required of food packaging. It protects food from damage and ensures food remains safe for consumption. Brands also use packaging to attract consumers' attention and to convey information.

Globally, packaging accounts for 31% of total plastic use (OECD 2022). Across all types of packaging, plastic dominates all other materials to a considerable degree, e.g. on the North American market, plastic packaging accounts for 43% of the market share of rigid containers (tubs, trays, jars, non-beverage bottles, drums etc.), 67% of flexible packaging (pouches, wrappers, bags, liners etc.), 72% of caps and closures and 100% of films (stretch and shrink wrap, stretch labels, sleeves etc.) (Franklin Associates 2018). The vast majority of plastic packaging is single-use, with 40% of global plastic waste made up of packaging (OECD 2022). Flexible and multi-layer plastics also make up a disproportionate share of plastic pollution, and are responsible for 80% of plastic leakage to the ocean (The Pew Charitable Trusts and Systemiq 2020).

Food packaging's ever-increasing reliance on single-use plastic formats along with the persistence of plastics in the environment, adds to the long-reaching – and as yet poorly characterized – impacts of plastic pollution on ecosystems and human health. The need for alternatives to single-use packaging is clear.

This report compares the environmental impacts of single-use plastic packaging versus alternative options for supermarket food, intended for home consumption[1]. The report is part of a series of meta-analyses of Life cycle assessment (LCA) studies that provides recommendations to policy makers on alternatives to commonly used single-use plastic products[2]. **Life cycle assessment (LCA)** is a well-established tool for assessing the potential environmental impacts associated with a product or service across its whole value chain.

Food packaging is well represented in the LCA literature. This meta-analysis focuses on recent (published within the last 10 years) comparative LCA studies that consider alternatives to single-use plastic packaging, amongst other criteria. Of the approximately 95 studies identified in the literature, **33 LCA studies** are analysed in depth in this meta-analysis, clustered by **three food archetypes**, namely Refrigerated products, Fresh produce and Pantry goods (Table E1). **Four cross-cutting themes** emerged from the analysis of the food packaging literature. These are i) the interplay between packaging and food waste, ii) the potential for bio-based and biodegradable plastics to replace conventional plastics, iii) the potential for reusable packaging systems, and iv) the lack of inclusion of the impacts of plastic packaging litter on the environment and human health.

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[1] LCA Recommendations for take-away food packaging are provided in a separate meta-analysis of the same series (UNEP 2020a).

[2] Previous products covered are bags, bottles, take-away food packaging, beverage cups, tableware, nappies, menstrual products and face masks. All these reports, including an integrative one, are available from https://www.lifecycleinitiative.org/single-use-plastic-products-studies/

Table E1: Overview of LCA studies assessed in the UNEP supermarket food packaging meta-analyses

	Refrigerated Products	Fresh Produce	Pantry goods	Broadly applicable packaging
Food products covered	Meat, dairy (cheese, yoghurt and milk) and dairy substitutes, desserts/prepared foods	Apples, tomatoes, carrots mangos, bread, fresh cut (melon) and lettuce	Olive oil, olives, honey, chocolate, tuna, long-life milk, pasta, rice, seeds, breakfast cereals, tofu, fruit bears	No food product specified
No. of studies	9	12	8	4
Packaging type covered	**Meat**: tray and wrap, tube/chub, modified atmosphere, skin, L-board **Dairy**: Pouch, pot/tub, carton, bottle, shrink wrap	**Prepared**: Film-sealed tub, film and pouch **Whole**: tray and wrap, plastic bag, clamshell **Transit**: Crate (single-use and reusable), box	**Shelf-stable**: glass bottle/jar (reusable), plastic bottle, carton (liquid), pouch, cup, can, wrapper **Dry goods**: plastic bag, carton, bag in box, bulk dispenser	Barrier films/plastic wraps
Geographies covered	Australia, Finland, Italy, Sweden and USA	Brazil, Canada, Finland, France, Germany, Italy, Netherlands, Spain, UK and USA	France, Germany, Italy, Spain, Sweden, Thailand	UK, Europe, USA, Thailand

Number of studies informing cross-cutting themes:

Food Waste	7	3	1	1
Bio-based plastics	3	3	-	4
Reusable packaging	1	8	4	-
Marine plastic litter*	1	-	-	-

* Marine plastic littler differs form the other cross-cutting themes as it is the lack of inclusion of the impacts of plastic packaging littler that is identified rather than this being covered in the studies (as with the food waste and bio-based and biodegradable plastics cross-cutting themes)

Based on the analysis of the 33 LCA studies and the wider LCA literature, most notably recent review studies, this report provides recommendations on supermarket food packaging per food archetype and per cross-cutting theme. The recommendations per food archetype are summarized in Table E2, in the form of a matrix.

KEY MESSAGES

- For foods associated with high environmental impacts in their production (e.g. meat) packaging design should prioritize minimization of food waste.
- For foods with lower environmental burdens in their production, packaging should be minimized and/or eliminated wherever feasible, i.e. wherever the impacts of potential increased food losses and/or logistics operations are not higher than the impacts of packaging avoided.
- **Wherever the food type allows it, food should be sold unpackaged or in reusable packaging,** as this is almost always environmentally preferred to food in single-use packaging.
- Life cycle assessments that cover the full value chain

and include product losses are needed in order to determine whether minimising, avoiding or using returnable or recyclable packaging leads to lowest environmental impacts overall.

- LCAs should be complemented with other analyses, such as on social impacts and gender analysis. Such analyses should include the potential for packaging to affect food safety (including differentiation of potential human health impacts by age and gender). Analyses on the potential for consumer behaviour to affect packaging impacts are also required, including acceptance by consumers of new formats and materials, likelihood to recycle or return (in the case of reusable packaging), and possibility of inappropriate use (leading to potential leaching of toxins into food).

Current legislative environments tend to favour single-use packaging systems. **Creating a level playing field is therefore essential for reusable packaging systems**. This can be done through:

- Economic measures that help remove market barriers for reusable packaging systems, such as taxes on packaging waste.
- Standards for food packaging that address overpackaging and require better packaging design.
- Legislation, such as Extended Producer Responsibility (EPR), that makes companies responsible for the end-of-life of the products they put on the market. Such legislation typically includes targets for recovery, recycling and/or recycled content. EPR legislation needs to include concrete measures to stimulate reuse, e.g. reuse targets, as this is lacking in most countries that have implemented EPR.

RECOMMENDATIONS FOR REUSABLE/RETURNABLE PACKAGING

The meta-analysis identifies the following recommendations to decrease emissions of returnable/reusable packaging and ensure their better performance over single-use packaging systems. The **recommendations** are primarily aimed at manufacturers, brand owners and retailers – as the potential developers and implementers of reusable packaging systems – but also at policy makers, in their capacity to provide the right support and enabling conditions.

- Consider the **whole packaging system when making decisions on reusable packaging**. “Packaging-free” consumer-facing solutions, such as dispensing dry goods from bulk refillable dispensers, are not necessarily the best environmental solution unless the bulk packaging used in the distribution of product to the point-of-sale is considerably more material-efficient than the traditional single-use packaging. Returnable packaging and reusable transit packaging (e.g. crates) can be a poor option when reverse logistics are inefficient, transport distances in the collection and redistribution of crates are high, the number or reuses are low, and washing/sanitizing requirements are high (or inefficiently carried out).
- **Washing/distribution plants should be widespread rather than a single, centralised plant** as this minimizes the average transport distance from user to inspection/cleaning and back to producer, thereby minimizing transport emissions. **Pooling**– where different companies share the same resource in order to optimize operations and costs – can be a mechanism to achieve this.
- Promote the **use of renewable energy in washing/reconditioning plants**, e.g. solar panels and Combined Heat and Power (CHP) plants in the operation of the facilities and the management of wastewater sludge and residues.
- **Encourage standardization of packaging**, as this facilitates **pooling** and **deposit return schemes** (in which a company/customer “rents” rather than owns the packaging). Both pooling and deposit return schemes have been shown to be highly effective in driving up return rates of reusable packaging and reducing emissions (through better logistics). It is recognised that standardization challenges traditional approaches to branding and product recognition, and brands will need to innovate to find new ways to promote products. Standardization of packaging also promotes recyclability through avoiding multiple colours, inks, different materials etc. and facilitates collection by reducing variability for collectors.
- **Reusable food packaging systems should be competitively priced with single-use ones.** Creating equitable pricing can be achieved through brand/retailer rewards, discount offers etc., and through legislation that creates the right economic incentives, e.g. tax breaks on products sold in reusable packaging.
- **Reusable food packaging systems must be accessible and convenient** to consumers to take the reusable option and to return the packaging. The use of smartphone apps and other technology, such as internet of things (IoT), including smart tags for tracking and tracing and verifying reuse rates, are already being used with great success in reusable packaging systems.
- A better understanding of gender roles, as well as consumer behaviours are essential to better drive the shift to reuse models. For instance, utilizing a gender lens to design different targeted communication and education strategies can enhance the information, motivation, and skills needed so that consumers can make better decisions around reuse, recycling and waste disposal, thereby unlocking long-term behavioural change.

RECOMMENDATIONS FOR SINGLE-USE PACKAGING

The meta-analysis yields the following general recommendations to improve the environmental sustainability of single-use supermarket food packaging:

- **Packaging material collection and recycling rates need to be drastically improved.** Conflicting LCA results for environmental preference between different packaging materials is largely a consequence of different waste management contexts. The LCA studies consistently show that higher recycled content in packaging materials leads to lower environmental impacts[3]. There is therefore a need for stronger regulations (e.g. on minimum recycled content and packaging design), as well as the development of packaging materials and recycling technologies that enable high recycled content in packaging materials whilst ensuring food safety. Achieving high recycled content in packaging also requires the availability of high quality recyclate (secondary material). To that end, **packaging needs to be designed for recycling.** Improvements in packaging design to address lack of recyclability include switching to single materials/ avoiding multi-layer and composite materials; removing dyes, pigments, and other chemical additives; and avoiding polymers that are difficult to recycle/lack recycling infrastructure.
- Consumers also need to be motivated to dispose of packaging responsibly. Behavioural research provides insight on how targeted communication and education strategies designed with a gender lens can enhance information, motivation and skills such that consumers recycle or otherwise dispose of packaging waste appropriately.
- **For food packaging that is contaminated with food waste and not easily cleaned, bio-based and biodegradable plastics[4] could present a solution for co-disposal of food waste and packaging** that results in overall lower climate change impacts, as long as the necessary infrastructure for collection and organic treatment of the waste is present[5]. Washing contaminated packaging increases both the costs and environmental impacts of mechanical recycling processes. Co-disposal of bio-based and biodegradable packaging with food waste removes the need to clean the plastic, but industrial composting requires waste management infrastructure to support the separate collection and treatment of this waste stream. Consumers also need to be amenable to sorting and separating their food packaging waste so that biodegradable plastics do not disrupt conventional plastics recycling systems or end up littered or in landfills (where they will have the same or higher impacts than conventional plastics). To this end, it is essential that any promotion/ support of biodegradable packaging comes with regulations for clear labelling, separation at source and standardization across packaging types so it is clear and simple for consumers to comply. For example, there is likely to be confusion if some films for meat are compostable and others are not, or if films for meat are compostable but not films for ready meals.
- **When changes are made to packaging designs with the intention to reduce their environmental impacts, it is important that the acceptability by consumers and the efficacy of the packaging be taken into consideration.** Where a packaging design causes higher indirect impacts, e.g. difficulty in extracting the full food content of the packaging (leading to higher food waste), any benefits of the packaging materials are likely to be overturned by the environmental impacts of the wasted food. Such indirect packaging design effects are currently not well reflected in LCA studies.
- **Packaging alternatives that seek to address marine plastic impacts should simultaneously address climate change impacts** (or at least not be at the expense of climate change impacts). Early findings integrating marine plastic litter impacts into life cycle impact assessment results indicate that climate change impacts are still likely to be the more important consideration for most packaging materials. **Preliminary indications of the preferred plastic material in terms of its physical effects on biota are that** expanded polystyrene (EPS) has the highest potential impacts and polylactic acid (PLA) the lowest. Polypropylene (PP) and high density polyethylene (HDPE) fall between these two, with PP found to have slightly lower potential impacts than HDPE in the case studies (although this finding may not be significant).

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[3] This finding relates only to mechanical recycling. None of the LCA studies covered in the meta-analysis looks at chemical recycling.

[4] Refer to Table 10 “What are “bio-plastics”?” of this report for terms and definitions.

[5] It is worth noting that when co-disposal with food waste is not a factor, it cannot be concluded that bio-based plastics always have lower climate change impacts than their fossil-fuel derived counterparts. The environmental impacts of bio-based plastics vary considerably with the bio-materials used in their production. Bio-based plastics produced with agricultural wastes as the feedstock are generally the best option as they avoid the environmental impacts of producing agricultural crops. Furthermore, bio-based plastics produced from agricultural wastes do not pose an indirect threat to food security, as is the case with those relying on food crops – most often maize – as a feedstock.

Table E2: Life cycle assessments of supermarket food packaging: what the science tells us

Waste and consumer system considerations

This matrix helps to identify the closest scenario and most environmentally sound options given a certain context.
The content of the matrix is simplified. Please refer to the full narrative of the meta-study for details.

🟦 Minimising food waste is a priority issue to be addressed through packaging

🟩 Food waste and packaging material are both important factors

▨ Packaging should be minimized/avoided/refillable/returnable

FOOD ARCHETYPE		Willing consumer and conducive legislative context (consumers willing and able to change behaviour related to purchasing, returning and recycling packaging)		Unwilling consumer and/or unfavorable legislative context (consumers unwilling or not able to change behaviour related to purchasing,	
		POOR WASTE MANAGEMENT (landfill and open dumping; poor/no clear intervention)	GOOD WASTE MANAGEMENT (high recovery and recycling rates)	POOR WASTE MANAGEMENT (landfill and open dumping; poor/no recycling or recovery)	GOOD WASTE MANAGEMENT (high recovery and recycling rates)
REFRIGERATED PRODUCTS	Meat products	**Minimize food waste** Packaging that extends shelf life*	**Minimize food waste** Packaging that extends shelf life AND Bio-based and biodegradable packaging to allow co-disposal of food waste	**Minimize food waste** Packaging that extends shelf life that doesn't affect consumer preferences leading to increased food waste Minimize packaging materials without increasing losses or breakages**	
	Dairy and its alternatives	**Minimize food waste OR reduce packaging materials** whichever results in greater benefits***			
	Desserts/ prepared foods	**Minimize food waste OR reduce packaging materials** whichever results in greater benefits			
FRESH PRODUCE	Fruit and vegetables: Ready-to-eat and easily damaged fresh fruits and vegetables.	**Minimize food waste** OR reduce packaging materials whichever results in greater benefits	**Minimize food waste** Packaging that extends shelf life AND Bio-based and biodegradable packaging to allow co-disposal of food waste with packaging	**Minimize food waste OR reduce packaging materials** whichever results in greater benefits	
	Whole fruit and veg, incl. transit packaging	**Avoid packaging** Fruit and vegetables sold loose; transported in reusable plastic crates	**Avoid packaging** Fruit and vegetables sold loose; transported in reusable plastic crates or cardboard boxes with high recycled content	**Minimize packaging** plastic bag or, for soft/ easily damaged produce PS tray and wrap; transported in reusable plastic crates	**High recycled content packaging** Plastic bag, or high-recycled content tray and wrap; transported in reusable plastic crates or cardboard boxes with high recycled content
PANTRY GOODS	Shelf-stable	**Returnable packaging**	**Returnable packaging** if returns are high and logistics optimized OR High recycled content packaging	**Minimize packaging** minimize materials and weight, e.g. plastic rather than glass or cardboard	**High recycled content packaging** that is itself recyclable
	Dry goods	**Avoid packaging** (product sold loose) provided bulk transport of product is material-efficient (e.g. reusable plastic crates)	**Avoid packaging** (product sold loose) provided bulk transport of product is material-efficient, e.g. reusable plastic crates or cardboard boxes with high recycled content	**Minimize packaging** minimize materials and weight. Avoid double packaging (e.g. bag in a box)	**High recycled content packaging** that is itself recyclable, e.g. cardboard carton

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* Packaging that extends shelf life includes that made of films with barrier properties and/or embedded with chemicals/nano-particles with specialised properties, and that in which products can be packed under vacuum, such as modified atmosphere packaging and skin packaging. Examples can be found in Sections 2.1.1 and 2.2.1.

** Reducing the weight of materials whilst retaining the properties of the packaging (commonly referred to as light-weighting) is an effective tactic to reduce environmental impacts since the materials are generally responsible for the highest share of direct impacts. However, it is essential that any indirect effects of light-weighting be taken into account, such as increased breakages, leading to higher food losses and higher environmental impacts overall.

*** Life cycle assessments that cover the full value chain and include product losses are needed in order to determine whether minimising packaging or extending shelf life leads to the lowest environmental impacts overall.

01

Introduction

Food packaging must fulfil several important functions: to keep food protected from physical damage that may impact quality; to provide a barrier to moisture, oxygen, bacteria and other contaminants and ensure the food remains safe for consumption; and to keep food fresh for longer and reduce food waste. In addition to these practical functions, packaging is also used to attract consumers attention, distinguish the product from other similar products and provide information on the contents, including nutritional information.

01

RESULTS FROM SUPERMARKET FOOD PACKAGING LIFE CYCLE ASSESSMENTS

The functions food packaging have to fulfil are complex and single-use plastics dominate food packaging due to their exceptional functional properties and relatively low production cost (FoodPrint 2020). Single-use plastic food packaging is now ubiquitous in society and there is hardly a part of the food value chain that is free from plastic. Packaging accounted for 31% of global plastics use in 2019 (OECD 2022).

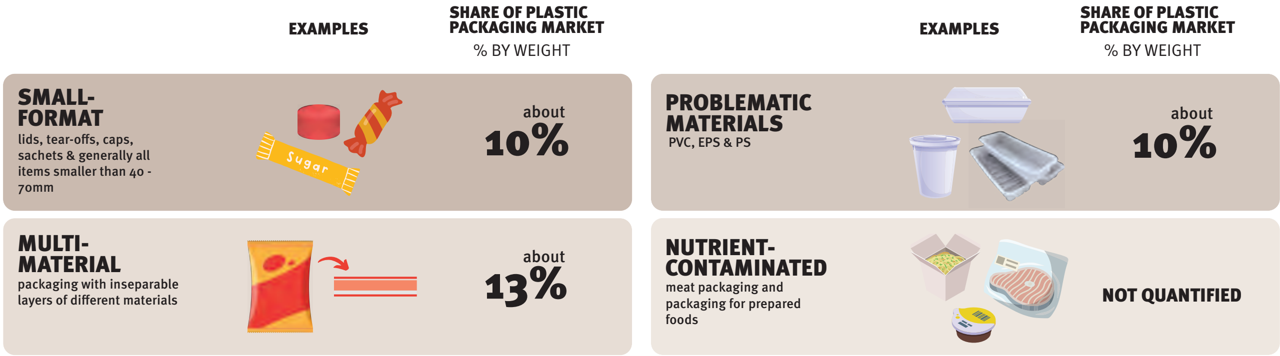
Across all packaging sectors, plastic dominates other materials to a considerable degree, e.g. on the North American market, plastic accounts for 43% of the market share of rigid containers (tubs, trays, jars, non-beverage bottles, drums etc.), 67% of flexible packaging (pouches, wrappers, bags, liners etc.), 72% of caps and closures and 100% of films (stretch and shrink wrap, stretch labels, sleeves etc.) (Franklin Associates 2018). The vast majority of this plastic packaging is single-use, with packaging representing 36% of municipal solid waste in Europe (Zero Waste Europe 2020) and plastic packaging making up 40% of global plastic waste (OECD 2022). Flexible and multi-layer plastics also make up a disproportionate share of plastic pollution, and are responsible for 80% of plastic leakage to the ocean (The Pew Charitable Trusts and Systemiq 2020).

Although convenient, single-use plastic packaging persists in the environment causing a significant waste challenge, with long-reaching and poorly understood impacts on the environment and human health (Center for International Environmental Law 2019). Countries are increasingly putting in measures to combat the high volumes of single-use plastic wastes, e.g. the vision of the European Plastics Strategy is that, by 2030 all plastic packaging placed on the EU market is either reusable or can be recycled in a cost-effective manner (European Commission 2018). The reality, however, is that recycling rates are far below what they need to be. Just 9% of plastics ever produced have been recycled, with less than 1% recycled more than once (Geyer, Jambeck, and Law 2017). Various types of single-use plastic food packaging present a particular challenge as they are not easily recycled. The World Economic Forum and Ellen MacArthur Foundation (2017) identify four **plastic packaging types that need fundamental redesign and innovation.** All these types are associated with food packaging, as shown in Figure 1:

- **Small-format packaging**: including sweet wrappers, yoghurt pots, lids, tear-offs and films. These items often escape collection or sorting systems ending up in the environment as litter. They generally are not considered for reuse and present challenges in recycling processes.
- **Multi-material packaging**: This type of packaging is commonly used in food packaging as multi-layer plastics provide enhanced barrier properties that protect food and prevent spoilage. Packaging made from multiple layers can be thinner than a similar packaging made from a single polymer, thus reducing weight and costs. However, multi-layer packaging is often difficult or impossible to recycle, particularly when plastics are combined with other materials (e.g. aluminium in chip/snack bags).
- **Problematic material packaging**: This includes the packaging materials polystyrene (PS), expanded polystyrene (EPS) and polyvinyl chloride (PVC), which are used extensively in food packaging trays and wraps. PVC, PS and EPS have poor collection and recycling rates even in developed economies and if not correctly sorted can contaminate other plastic recycling processes.
- **Nutrient-contaminated packaging**: Meat packaging and packaging for prepared foods are often contaminated with food after use. This can hamper recycling efforts at the home as food residues may be difficult, unpleasant, or time-consuming to remove from packaging. Packaging contaminated with organics also present technical challenges to collection, sorting and recycling processes.

To assist consumers, producers, retailers and policy makers in making informed choices about single-use supermarket food packaging and their alternatives, this report is a meta-analysis that summarizes current knowledge about the life cycle environmental performance of single-use and reusable supermarket food packaging systems. The report is the ninth in a series of reports that provide insights from life cycle assessments (LCA) to make more informed policy decisions around single-use plastic products (SUPP) and their alternatives[6]. The series fulfils the request to UNEP under Resolution 9 of the fourth edition of the United Nations Environment Assembly (UNEA4) in March 2019, on "Addressing single-use plastic products pollution" (UNEP/EA.4/R.9), which "encourages member states to take actions, as appropriate, to promote the identification and development of environmentally-friendly alternatives to single-use plastic products, taking into account the full life cycle implications of those alternatives". The recent resolution at the UN Environment Assembly (UNEA-5) to End Plastic Pollution and forge an international legally binding agreement by 2024 places even further relevance on understanding the full life cycle implications of alternatives to single-use plastic products.

Figure 1: Packaging types that require fundamental redesign and innovation. Adapted from World Economic Forum and Ellen MacArthur Foundation (2017)



1.1 OVERVIEW OF LCA AND ITS APPLICATION TO FOOD PACKAGING

Life Cycle Assessment (LCA) is a tool used to measure the environmental impacts of a product's life cycle. It represents a well-developed framework that can be used to guide environmental decisions, governed by international and national standards and guidelines[7]. Specifically, LCA enables decision makers to evaluate the environmental performance of a product system in terms of all the steps related to creating that product, from agricultural processes and raw material extraction, transportation, processing and manufacturing, through retail and distribution, to the end-of-life management of products and materials. LCA thus enables decision makers to avoid shifting the burden from one of these life cycle stages to another. The **food packaging life cycle** is depicted in Figure 2.

A further way an LCA avoids burden shifting, is that it quantifies the multiple potential environmental impacts that a product system may have. In this way, a decision maker can understand what trade-offs may need to be made between environmental impacts. A number of life cycle impact assessment (LCIA) methods have been developed, usually orientated around addressing common areas of concern, such as human health, ecosystem quality and resource depletion. Further details on the LCA method are given in Appendix A.

LCAs provide important insights for policymakers but these need to be supplemented with a range of additional considerations that are not accounted for in LCA studies. Social aspects as well as gender norms and considerations are aspects not addressed by environmental LCAs that need careful attention when comparing different packaging options and their use (UNEP 2021b).

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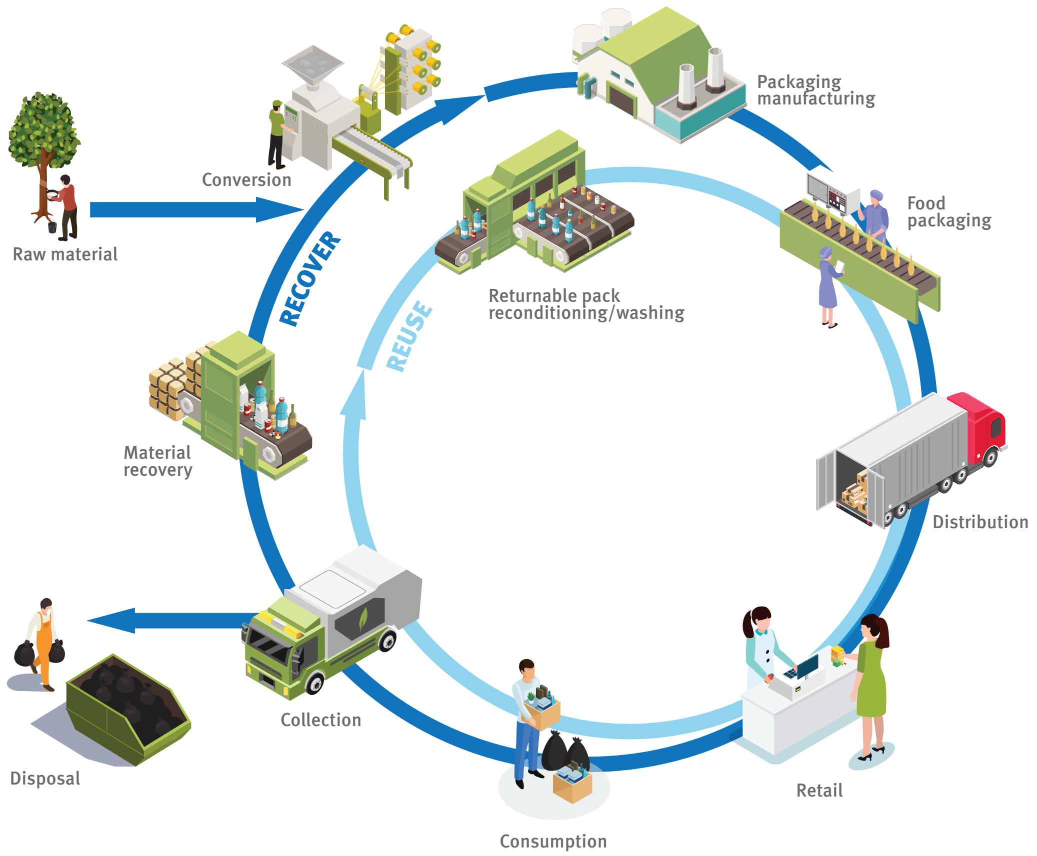
[6] Previous products covered are bags, bottles, take-away food packaging, beverage cups, tableware, nappies, menstrual products and face masks. All of these reports are available from https://www.lifecycleinitiative.org/single-use-plastic-products-studies/

[7] E.g. ISO, Environmental management — Life cycle assessment — Principles and framework, 14040:2006; ISO, Environmental management — Life cycle assessment — Requirements and guidelines, 14044:2006; JRC-IES (2010) International Reference Life Cycle Data System (ILCD) Handbook. General guide for Life Cycle Assessment – Detailed guidance. European Commission, Joint Research Centre's Institute for Environment and Sustainability, Ispra, IT.

Figure 2: The life cycle of food packaging



LCA has been applied extensively in assessing food packaging systems (Flanigan, Frischknecht, and Montalbo 2013), where it has been shown to have both strengths and weaknesses (Schweitzer, Petsinaris, and Gionfra 2018). The principal strength of LCA is its "systems view", taking into account all stages and processes involved in delivering the packaging service, e.g. transport packaging (secondary boxes and pallets), and return trips and washing in the case of reusable packaging systems. Furthermore – even though it is not always done – LCA can address the packaging together with the food product it is intended to deliver, thereby ensuring the whole system is improved and not just the packaging. This is important, as the packaging impact can be small in the context of the wider food product system (the issue of food waste in packaging LCAs is covered in Section 3.1 of this report).

A weakness of LCAs – and all models – is their representation of a simplified reality. This is especially important in modelling end-of-life management. LCAs tend to model scenarios, e.g. a material is landfilled or recycled, or a country-specific snapshot, e.g. 20% recycled, 35% incinerated with energy recovery and 45% landfilled. Few (if any) packaging LCAs assess the potential for packaging to be littered or mishandled, e.g. burnt in an open dump. The current inability of LCA to address the impacts of plastics (and other materials) in the marine environment is a well-recognised limitation of LCA (this issue is given special attention in Section 3.4 of this report). Concerns surrounding the leaching of chemicals from plastics in the environment and those emitted when plastics are burnt are important to address. Adverse health impacts arising from plastics in the environment are not currently captured in LCA studies, partly because of a lack of inventory data, e.g. a lack of disclosure on additives in plastics, and partly because of a lack of understanding on the mechanisms for chemicals to leach from plastics and for humans to be exposed, as well as on the health consequences of exposure. Furthermore, adverse health impacts from chemicals in plastics are not equally distributed across the population, with pregnant women (and their unborn), very young children, as well as girls and boys undergoing puberty, especially susceptible (SAICM 2017).

Also problematic is whether a material modelled as being recycled actually delivers the benefits it is credited with in the LCA. This can be highly context specific and vary over time, as it had to do with whether there is demand for the recycled material (which in turn depends on, amongst other factors, the quality of the recyclate, and the relative price of primary and secondary materials). This is important as the end-of-life credits (also called avoided burdens) assigned to materials for energy recovery or recycling can be very influential in packaging studies.

Furthermore, whilst LCA aims to cover a full suite of relevant environmental impacts, there tends to be an emphasis on climate change impact. This is partly for ease of communicating study results, but also because greenhouse gas emissions tend to be more certain and easier to calculate, than, for example, trace amounts of toxic chemicals. The tendency to focus on climate change, together with weaknesses in modelling end-of-life, has led to packaging LCAs tending to favour complex materials that cannot be recycled, such as multi-layered plastics (Schweitzer, Petsinaris, and Gionfra 2018).

Finally, it is good to bear in mind that LCA studies assess the direct environmental impacts of packaging. Whilst there is a strong recognition in the literature that packaging studies need to take into account food losses, i.e. to look at the food delivery system including the food product, the complexity that this introduces into packaging LCA studies means that this is still not the norm. Even where the food product is included in the LCA, a lack of data, e.g. on the influence of packaging characteristics (shape, type of material etc.) on consumer behaviour, means that studies are not able to fully take into account the indirect environmental impacts of packaging. This is important, as consumer behaviour and how this relates to food waste can be a far higher driver of environmental impacts than the direct impacts of the packaging materials (Molina-Besch, Wikström, and Williams 2019).

A further indirect impact not covered by LCA studies is how consumer behaviours relate to packaging safety. Food-contact packaging is well regulated in most countries and plastic containers are stable and safe if used properly. However, there are instances where consumer behaviour can lead to additives and other toxins leaching out of packaging into food (New Zealand Ministry for Primary Industries 2020). For example, where containers not designed for reuse are used multiple times and start to degrade (especially if washed at high temperatures between uses), food Is heated up in packaging not designed to be heated (e.g. plastic wrap), and packaging - even that designed for reuse - is washed not in accordance with manufacturers' instructions (e.g. with bleach or harsh detergents). Early indications are that adverse health outcomes arising from exposure to chemicals in food, including those from chemicals potentially leached from plastic packaging, are not equally distributed in the human population. Certain ages and genders are more susceptible than others, both in their exposures and in their health consequences (UNEP 2016).

There are significant information gaps surrounding chemical releases from plastic packaging and their potential long-term health impacts, especially with regards to the gender-, age- and income-differentiation of these impacts (Women Engage for a Common Future 2017, UNEP 2016). Further research into the impacts of chemicals leaching from plastic packaging on the health of different consumer groups is needed. Such information is crucial not only in policy formulation but also in improving packaging practices as well as formulating public health messages. LCA does not differentiate health impacts (or any other of the impacts it considers) according to gender, age or income. Furthermore, risk is not an element captured by LCA, i.e. the low probability but high consequences of exposure given certain behaviours or circumstances. Nonetheless, these are important considerations, which along with the considerations discussed above, clearly point to the importance of not basing decisions on food packaging on the findings of LCA studies alone.

1.2 METHODOLOGY FOR SELECTION OF LCA STUDIES

Supermarket food packaging is a broad topic that is well covered in the LCA literature. While not all food LCAs specifically consider packaging alternatives, they do mostly include the environmental impacts of packaging. Kan and Miller (2022) and Licciardello (2017) provide an overview of the diversity of food types covered in the literature. Given the wealth of available literature, this meta-analysis focuses on more recent studies and those studies that consider alternatives to single-use plastic food packaging. The specific criteria for inclusion of LCAs in the meta-analysis are listed in Table 1. However, whilst these criteria define the selection of the 33 LCA studies included in the meta-analysis, **a large number of review studies and the wider relevant literature were also consulted and inform the findings and recommendations of this report.**

To identify relevant LCAs on food packaging, searches were initially performed on Web of Science to locate relevant peer-reviewed studies published in the last ten years. Thereafter, further searches were performed using Google Scholar and Google to ensure that the literature search was comprehensive and included both academic literature and company- and industry-sponsored LCA studies. A webinar with over 50 technical experts from academic, industry and civil society was held in December 2021, to obtain feedback on the literature compiled, and invite further suggestions for inclusion.

The webinar was also used as an opportunity to obtain feedback on the proposed criteria for inclusion of LCAs in the meta-analysis (Table 1), the categorization of food packaging by food type (as shown in Figure 3), and the use of the term "supermarket food packaging" to broadly apply to all food packaged and intended for purchase by consumers for home consumption (as distinct from take-away food purchases, which is covered in a separate meta-analysis (UNEP 2020a)).

01 RESULTS FROM SUPERMARKET FOOD PACKAGING LIFE CYCLE ASSESSMENTS

Table 1: Criteria for inclusion of LCA studies in the food packaging meta-analysis

Criterion	Conditions for inclusion in meta-study
Types of products covered	Study must consider more than one food packaging option, preferably including reusable alternatives and/or alternative materials to fossil-based plastic
Completeness – life cycle	Study must be a full LCA study, i.e. cover all life cycle stages (raw materials to disposal), preferably also considering food waste in the system boundary
Completeness – indicators	Study must consider a range of potential impacts, i.e. not just be a carbon footprint
Transparency	Sufficient information must be made available in the study report/article to interpret the study findings, including information on methodological assumptions, data sources and impact assessment methods
Age of study	Studies must be published within the last ten years, i.e. in the period 2011 to 2021
Peer review	Industry-commissioned studies must have undergone peer review. Academic studies published in peer-reviewed journals
Geographic coverage	Studies may be selected on geographical coverage in order for the meta-analysis to cover a range of countries and different levels of economic development
Language	Studies need to be available in English

The initial survey of the literature identified over 95 studies that fell under the broad topic of food packaging and life cycle assessment. From the approximately 70 studies comparing food packaging alternatives using life cycle assessment, 25 studies fully met the criteria for inclusion in the meta-analysis (Table 1). Studies were eliminated primarily because they were published pre-2010 or looked only at carbon footprint or a reduced set of indicators. A decision to include 8 studies that partially met the criteria was made on a case-by-case basis as these studies provided insights not provided by any of the other studies (see the individual study summaries in Appendix C for details).

The **33 studies selected for inclusion in the meta-analysis** were organised into three food archetypes, namely Refrigerated products, Fresh produce and Pantry goods (Figure 3). Four of the studies considered food packaging more broadly, in that they looked at films/wraps that are used in a wide array of supermarket food packaging. An overview of the studies included in the meta-analysis and the food types, packaging types and topics covered by them is provided in Table 2. Most of the packaging types were business-to-consumer (B2C) packaging, except for the studies on whole fruit and vegetables and bread, which looked at business to business (B2B) packaging. These examples of B2B packaging were included in the meta-analysis as whole fruit and vegetables can be sold loose to the consumer, which makes the crate or box the primary packaging associated with this type of food (WRAP 2022).

Figure 3: Supermarket food archetypes considered in the meta-analysis

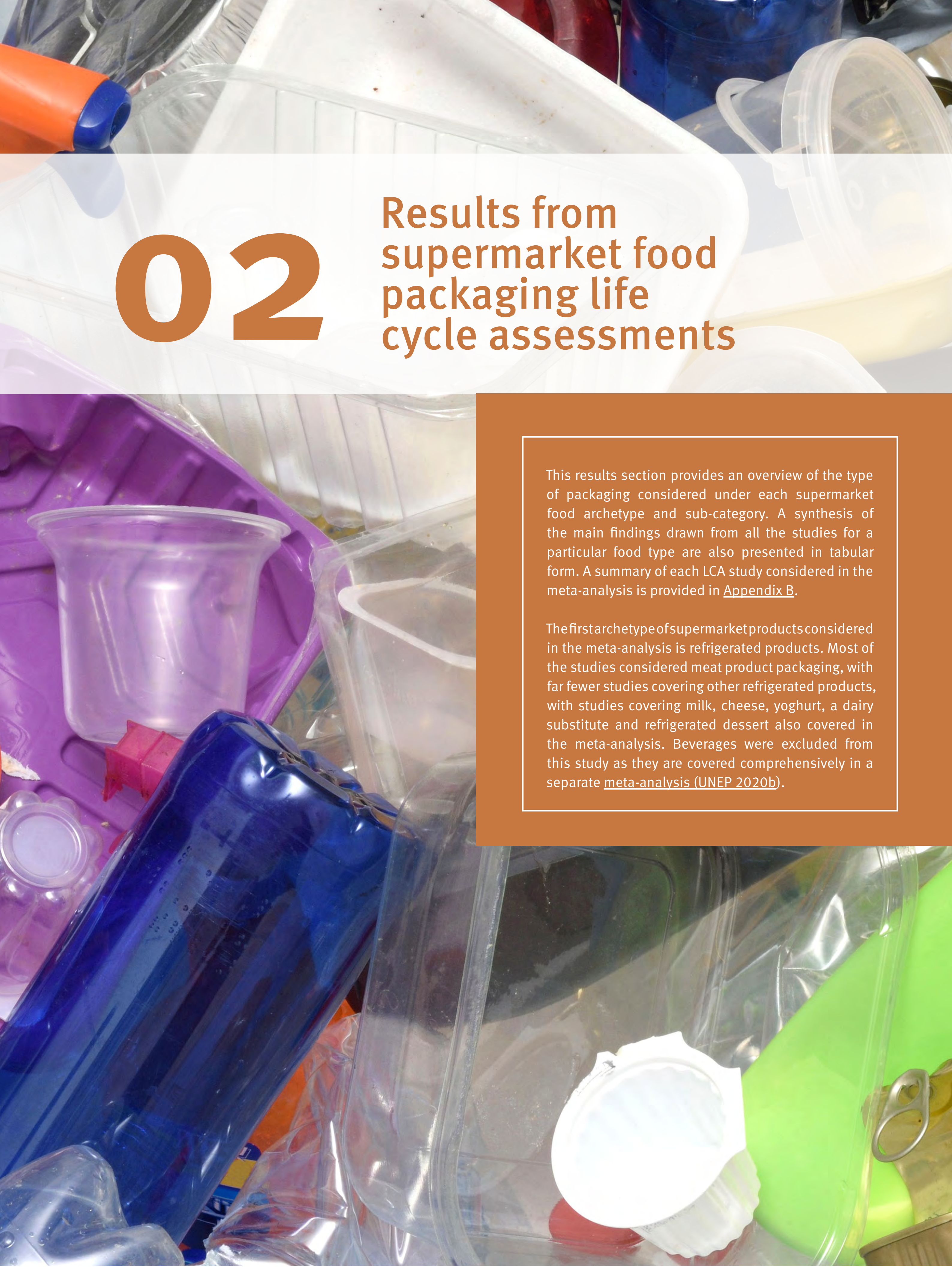
	Refrigerated Products	**Fresh Produce**	**Pantry goods**	**Broadly applicable packaging**
Food products covered	Meat, dairy (cheese, yoghurt and milk) and dairy substitutes, desserts/prepared foods	Apples, tomatoes, carrots mangos, bread, fresh cut (melon) and lettuce	Olive oil, olives, honey, chocolate, tuna, long-life milk, pasta, rice, seeds, breakfast cereals, tofu, fruit bears	No food product specified

Table 2: Number of studies covered in the meta-analysis categorized according to three food archetypes and whether the study informs the four cross-cutting themes

Food Archetype and product	**Packaging types considered**	**Total number of studies covered in meta-analysis**	**Number of studies meeting all criteria**	**Number of studies partially meeting criteria**	**Number of studies addressing the cross-cutting theme***			
					Food waste	Bio-based and bio-degradable plastics	Reusable	Marine plastic litter**
Refrigerated products								
Meat	Single-use	5	2	3	3	2	-	-
Dairy and dairy substitutes	Single-use / Reusable	4	1	3	3	1	1	1
Prepared foods (dessert)	Single-use	1	1	-	1	-	-	-
Fresh produce								
Ready-to-eat fresh fruit and vegetables (cut melon, lettuce)	Single-use	2	2	-	2	2	-	-
Whole fruit and vegetables	Single-use / Reusable	3	2	1	1	1	1	-
Transit packaging for fruit, vegetables and bread	Single-use / Reusable	7	7	-	-	-	7	-
Pantry Goods								
Shelf-stable food products (olive oil, long-life milk, olives, honey, tuna, tofu)	Single-use / Returnable	7	6	1	1	-	2	-
Dry goods (pasta, rice, cereal, chia seeds, fruit bears)	Single-use / Refillable	2	2	-	-	-	2	-
Broadly applicable packaging								
Films for food packaging / barrier wraps (food product not specified as applicable to a range of food products)	Single-use	4	2	2	1	4	-	-
Total number of studies covered in the meta-analysis		**33****[**]**	**24**	**9**	**12**	**10**	**13**	**1**

* The total number of studies is less than the sum of the individual food products because two of the studies address more than one food product.

** Marine plastic litter differs from the other cross-cutting themes as it is the lack of inclusion of the impacts of plastic packaging litter that is identified rather than this being covered in the studies (as with the food waste and bio-based and biodegradable plastics cross-cutting themes)



02

Results from supermarket food packaging life cycle assessments

This results section provides an overview of the type of packaging considered under each supermarket food archetype and sub-category. A synthesis of the main findings drawn from all the studies for a particular food type are also presented in tabular form. A summary of each LCA study considered in the meta-analysis is provided in Appendix B.

The first archetype of supermarket products considered in the meta-analysis is refrigerated products. Most of the studies considered meat product packaging, with far fewer studies covering other refrigerated products, with studies covering milk, cheese, yoghurt, a dairy substitute and refrigerated dessert also covered in the meta-analysis. Beverages were excluded from this study as they are covered comprehensively in a separate meta-analysis (UNEP 2020b).

TYPES OF PACKAGING FOR REFRIGERATED PRODUCTS COVERED IN THE LCA STUDIES

Meat packaging

Plastic tray and wrap

Chub/tube

Modified atmosphere packaging (sealed plastic tray)

Skin packaging (vacuum sealed plastic)

L-board packaging (plastic and laminated cardboard)

Dairy and dairy-substitutes packaging

Laminate pouch (portion size)

Plastic bottle (PET)

6-pack plastic tubs (PS) (portion size)

Plastic tub (PP) (bulk size)

Returnable glass bottle

Sealed plastic wrap

Aseptic carton (liquid packaging board)

Plastic cup (PP) with aluminium cover

Prepared food packaging

Sealed tray and wrap (modified atmosphere packaging)

LIFE CYCLE ASSESSMENTS OF PACKAGING FOR REFRIGERATED FOODS: WHAT THE SCIENCE TELLS US

Preferred type of packaging for refrigerated food products depending on context

The content of the matrix is simplified and aims to summarise the narrative of this section. Please refer to the full narrative of Section 3.1 for details.

	Willing consumer and conducive legislative context (consumers willing and able to change behaviour related to purchasing, returning and recycling packaging)		**Unwilling consumer and/or unfavorable legislative context** (consumers unwilling or not able to change behaviour related to purchasing, returning and recycling packaging)	
	POOR WASTE MANAGEMENT (landfill and open dumping; poor/no recycling or recovery)	**GOOD WASTE MANAGEMENT** (high recovery and recycling rates)	**POOR WASTE MANAGEMENT** (landfill and open dumping; poor/no recycling or recovery)	**GOOD WASTE MANAGEMENT** (high recovery and recycling rates)
Meat products	**Minimize food waste** Packaging that extends shelf life*	**Minimize food waste** Packaging that extends shelf life AND Bio-based and biodegradable packaging to allow co-disposal of food waste	**Minimize food waste** Packaging that extends shelf life that doesn't affect consumer preferences leading to increased food waste Minimize packaging materials without increasing losses or breakages**	
Dairy and dairy alternatives	**Minimize food waste OR reduce packaging materials** whichever results in greater benefits***			
Desserts/ prepared foods	**Minimize food waste OR reduce packaging materials** whichever results in greater benefits			

🟦 **Minimising food waste is a priority issue to be addressed through packaging**

🟩 **Food waste and packaging material are both important factors**

* Product photography by Rothko Brand Partners and sourced online

02 RESULTS FROM SUPERMARKET FOOD PACKAGING LIFE CYCLE ASSESSMENTS

2.1 PACKAGING FOR REFRIGERATED PRODUCTS

2.1.1 Packaging for meat products

All meat packaging considered in the meta-analysis is business to consumer (B2C) packaging and single-use. Reusable B2C packaging is not found for this food sub-category.

The **most common type** of meat packaging is a **plastic tray with a plastic film overwrap**. The plastic tray can be made from a variety of materials: polystyrene (PS), polyethylene (PE), polypropylene (PP), bio-based plastics (both biodegradable and non-biodegradable) or multi-layer materials, e.g. polystyrene-ethylene vinyl alcohol (PS-EVOH), polyethylene terephthalate-polyethylene (PET-PE). The wrap is most often low density polyethylene (LDPE), but multi-layer plastics can be considered for their barrier properties. In some cases, an absorber pad made from cellulose or other material is included.

Modified atmosphere packaging (MAP), as the name suggests, involves changing the atmosphere around the meat product by removing oxygen to slow spoilage and increase shelf life. MAP also consists of a plastic tray with the tray sealed with a plastic film.

The first archetype of supermarket products considered in the meta-analysis is refrigerated products. Most of the studies considered meat product packaging, with far fewer studies covering other refrigerated products, with studies covering milk, cheese, yoghurt, a dairy substitute and refrigerated dessert also covered in the meta-analysis. Beverages were excluded from this study as they are covered comprehensively in a separate meta-analysis (UNEP 2020b).

Chub or tube packaging is often used for ground or processed meats. Here the meat is packed under vacuum in a tube of plastic, which is sealed on both ends with a metal clip.

Skin packaging, is another type of vacuum packaging for meat, where the meat is placed on a plastic or paperboard shallow tray and a plastic film is vacuum sealed around the product removing air. **L-board** packaging is a type of skin packaging for bacon and the likes, and consists of polyethylene/wax coated paper/polyethylene that includes a flap over the product together with an overwrap pouch. "OLB-board"[8] is similar, but the packaging is made of expanded polystyrene/oriented polypropylene together with a lighter weight pouch.

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[8] This type of packaging is not standard in the market, but is an alternative packaging type that was considered in one of the studies.

Table 3: Overview of LCA studies on meat packaging.

The option with the lowest impact on climate change shaded green.*

Environmental impact of biodegradable food packaging when considering food waste**
Dilkes-Hoffman et al. (2018)

The premise of this paper is that biodegradable plastic packaging has a role to play in replacing conventional multi-layer plastic packaging that is non-recyclable and non-degradable.		**Functional unit:** 1 kg of packaged product at the house **Geographic scope:** Australia
Traditional packaging	Bio-based and biodegradable packaging	Main conclusions
🟩 PP tray	Bio-based polymer tray (thermoplastic starch (TSH)/ polylactic acid (PLA))	Although the conventional plastic packaging performed slightly better under the set of assumptions used in the study, **food waste was seen to dominate the overall results, with the contribution of packaging negligible** in comparison. The bio-based packaging if landfilled will degrade to methane, but emissions can be reduced through methane capture or other end-of-life alternatives. **If bio-based polymers extend shelf life and reduce food waste by as little as 6% then they would have similar greenhouse gas (GHG) impacts to fossil-based plastic packaging**.

Comparison of bacon packaging on a life cycle basis: A case study
Kang et al. (2013)

The objective of this study is to evaluate the environmental effects of reducing the mass of traditional bacon packaging compared to substituting with new packaging material.		**Functional unit:** Packaging for 1,000lb of bacon **Geographic scope:** US
Traditional packaging (Single-use)	Light weight packaging (Single-use)	Main conclusions
L-board packaging (PE/wax board/PE)	🟩 OLB-board (EPS/PP)	**For the traditional L-board packaging, light weighting reduces environmental impact proportionally.** Even so, the light weighting only applied to the board itself and not the PE/nylon pouch, which remained unchanged. The alternative OLB packaging is still lighter than the 50% reduced traditional packaging. As such, the environmental impacts for the OLB-board packaging are improved across all impact categories, with the exception of mineral extraction.
L-board packaging with 25% mass reduction		
L-board packaging with 50% mass reduction		

* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

** The relatively few studies considering bio-based and biodegradable plastics led to the decision to include this study in the meta-analysis even though it does not fully meet the selection criteria (it considers only greenhouse gas emissions and water use).

Table 3: Continued – Overview of LCA studies on meat packaging.

The option with the lowest impact on climate change shaded green.*

Life cycle assessment of food packaging and waste: Phase 2: Case study results[**]
Heller et al. (2016)

This study investigates the trade-offs in environmental impact between food waste and food packaging, and by doing so unpacks the role that packaging plays in controlling food waste. The three case studies focus specifically on food waste at the retail and consumer levels for 1kg of beef products consumed, drawing on data from retailers on actual food waste rates according to packaging type.

Functional unit: 1 kg of beef consumed

Geographic scope: USA

Traditional packaging (Single-use)	Extended shelf life or light weight packaging (Single-use)	Main conclusions
Case 1a:		 
PS tray with overwrap	High oxygen modified atmosphere packaging (hi O_2 MAP) PP tray	**When the food waste levels are similar, there is not a clear preferred packaging option**. However, if the consumer waste level is assumed to decrease due to the MAP extending shelf life on the consumer side, then the MAP performs better.
Case 1b:		  
Variety of polystyrene trays with LDPE overwrap for different products	Chub packaging hi O_2 MAP, PP tray with film	The packaging types were difficult to compare directly as they contained a range of different beef products. The study did however, show that GHG emissions follow food wastage rates, with **higher impacts seen with higher food wastage rates.** An important observation is that there are many other factors, besides packaging, that impact retail food waste. These relate to the demand for a particular product, consumer preference, product turnaround, price and in-store marketing aspects.
Case 1c:		 
EPS tray and wrap	Skin packaging	**The skin packaging significantly reduced food waste and as a result had significantly lower impacts.**

* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

** The fact that his study considers actual food waste rates at the retail level led to the decision to include it in the meta-analysis even though it does not fully meet the selection criteria (it considers only greenhouse gas emissions and cumulative energy).

Table 3: Continued – Overview of LCA studies on meat packaging.

The option with the lowest impact on climate change shaded green.*

A comparative life cycle assessment of meat trays made of various packaging materials *Maga, Hiebel and Aryan* (2019)

The objective of this study is to evaluate the environmental impacts of different meat trays currently in use in Europe. The focus is on recyclability as well as recycled content.		**Functional unit:** A tray with a volume of about 1 litre for preserving 500g fresh meat **Geographic scope:** Germany
Single material packaging (Single-use)	Multi-layer packaging (Single-use)	Main conclusions
Extruded polystyrene (XPS) closed cell tray	XPS-EVOH tray	**Due to their lighter weight, all XPS trays had lower impacts than PP, PLA and PET trays,** for all impact categories with the exception of resource depletion. **Multi-layer packaging was seen to have higher environmental impacts than trays made from a single material.** PLA packaging performed the worst of all the packaging types.
🟩 XPS open cell tray		
Recycled polyethylene terephthalate (rPET) tray	PS-EVOH tray	
Amorphous polyethylene terephthalate (APET) tray		
PP tray	rPET-PE tray	
PLA tray		

The influence of packaging attributes on recycling and food waste behaviour – An environmental comparison of two packaging alternatives** *Wikström, Williams, and Venkatesh* (2016)

Historically, many LCAs on food packaging focused on the direct impacts of food packaging, without considering the indirect impacts associated with recycling and food waste. Both factors are strongly influenced by consumer behaviour. This study focuses on the impact of these factors on the overall performance of the packaging from a life cycle perspective.		**Functional unit:** 1 kg of eaten mincemeat **Geographic scope:** Sweden
Traditional packaging (Single-use)	Light-weight packaging (Single-use)	Main conclusions
PET tray, LDPE overwrap (excluding food waste)	🟩 Polyamide tube, aluminium clip (excluding food waste)	If just the packaging is compared, then the lightweight polyamide tube packaging performs better than the traditional meat tray. However, the tube packaging is difficult to empty and clean with the result that food waste is largely unavoidable. **If food waste is included in the impacts, then the tray packaging, which is easily emptied and cleaned performs more favourably.**
🟩 PET tray, LDPE overwrap (including food waste)	Polyamide tube, aluminium clip (including food waste)	

* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

** The relatively few studies focussing on food waste and end-of-life (recycling) led to the decision to include this study in the meta-analysis even though it does not fully meet the selection criteria (it considers only global warming, acidification and ozone depletion).

02 RESULTS FROM SUPERMARKET FOOD PACKAGING LIFE CYCLE ASSESSMENTS

When comparing just the packaging of meat products, the results show that **light weight packaging improves environmental performance as it reduces impacts across the life cycle, due to reduced material demand and production, lower transport requirements and reduced waste at end-of-life.** This is confirmed by the study of Maga, Hiebel and Aryan (2019), which compares nine different meat trays. In this study, due to their lighter weight, all XPS trays have lower impacts than PP, PLA and PET trays for all investigated impact categories, apart from resource depletion. In addition, **multi-layer packaging seem to have higher environmental impacts than trays made from a single material**. The same trends were observed in the study on bacon packaging (Kang *et al.* 2013), with the lighter multi-layer EPS packaging performing better across all categories (except mineral extraction) than the heavier conventional multi-layer paper board packaging.

Packaging made from bio-based and biodegradable plastic seem to perform worse overall, compared to fossil-based plastics. This is the case for the study by Maga, Hiebel, and Aryan (2019) and Dilkes-Hoffman *et al.* (2018), with the latter study only considering greenhouse gas (GHG) emissions. Although the production related impacts were comparable (for energy use and GHG emissions), bio-based plastics have additional impacts associated with agricultural production (e.g. from fertilizer use and land occupation), whereas fossil-based plastics perform poorly in terms of resource depletion. At end-of-life, bio-based and biodegradable plastic packaging sent to landfill will degrade and release methane, which if not captured can lead to further greenhouse gas emissions.

For meat products, the environmental impact of the food product dominates the overall environmental impact, with the contribution of packaging being relatively small (Licciardello 2017; Heller, Selke, and Keoleian 2019). **It is therefore critical to include food waste in the assessment of meat packaging. This is because the environmental impacts associated with the food waste can often overshadow the differences in packaging environmental impacts.** The work of Wikström and Williams demonstrates the importance of **considering food waste in food packaging design** (Williams and Wikström 2011; Williams *et al.* 2012; Wikström *et al.* 2014; Molina-Besch, Wikström, and Williams 2019). Important contributions to the field of Life Cycle Assessment in this regard relate to **defining a functional unit based on the food eaten to account for food waste in distribution, retail and in the household.** Many of the more recent studies consider the impact of food waste when comparing meat packaging options, including the studies on mincemeat (Wikström *et al.* 2014), beef packaging (Heller *et al.* 2016; Dilkes-Hoffman *et al.* 2018), ham packaging (Silvenius *et al.* 2011), and turkey packaging (Heller *et al.* 2016).

In many of these studies, there is a trade-off between the reduction in food waste associated with the use of alternative packaging (including both new packaging designs and new packaging materials) and the increased environmental impacts associated with such alternative packaging; whether it be using bio-based and biodegradable materials in the case of Dilkes-Hoffman *et al.* (2018), or modified atmosphere packaging (MAP) in the case of Heller *et al.* (2016). **In general, the greater the reduction in food waste compared to the traditional packaging the greater the overall benefit in switching to the new packaging design and alternative materials.** However, if the alternative packaging increases food waste (as in the study of Wikström, Williams and Venkatesh (2016), where a lightweight tube packaging was compared to the traditional tray and wrap), then the traditional packaging is preferred. **Thus, the determining factor in many studies is the difference in generation or avoidance of food waste rather than the properties of the packaging itself.**

The results of these studies on new packaging designs and alternative materials were dependent on assumptions regarding food waste generation at the retail and consumer level, for which there is often very little information available. Molina-Besch, Wikström and Williams (2019) identify the following as important areas of research to support future packaging life cycle assessment studies: the influence of packaging on consumer behaviour in terms of how they transport, store and prepare food and how they clean, separate and dispose of packaging and food waste. Shelf life studies are also important to accurately determine the extent to which alternative packaging extends shelf life at both the retailer and household. As noted by Heller *et al.* (2016), however, there are myriad other factors that can impact shelf life beyond the properties of the packaging itself including consumer demand for a particular product, consumer preferences, product turnaround, price and in-store marketing aspects. Thus, **consumer education needs to accompany changes in packaging design.**

Recommendations for meat packaging

- Meat packaging should be **designed to reduce food waste** at both the retail and consumer level. Where new packaging is introduced that impacts on the consumer preferences for the product, consumer education is required to ensure that the technical packaging improvements achieve the desired outcomes.
- For meat packaging alternatives that perform equivalently in terms of food waste, **light weight packaging** (often polystyrene) is preferred due to the proportionally lower impacts associated with lighter weight plastic packaging. Similarly, **single material packaging** is preferred over multi-layer packaging.
- Before alternative meat packaging is introduced to the market, it should be assessed through an LCA to ensure that any environmental benefits are realised. Importantly, the definition of the functional unit should allow food wastage to be included in the assessment (i.e. expressed in terms of food consumed) so that the food wasted at the consumer level is taken into account. This may require additional research to understand how the packaging impacts **consumer behaviour**, in terms of food storage and use, as well as the likelihood of cleaning, separation and sorting of the packaging after use. The latter is important to determine the actual end-of-life treatment of the packaging, as meat packaging is less likely to be recycled than other plastic packaging, and average plastic recycling rates will likely overestimate any recycling benefits (and consequently underestimate end-of-life disposal impacts).

2.1.2 Packaging for dairy and dairy substitutes

As with meat product packaging, the majority of LCA studies for dairy and dairy-substitute packaging, only considers **single-use packaging** with **no reusable packaging or returnable models investigated.** The exception is fresh milk, in which returnable glass bottles are investigated. The studies considered for this meta-analysis focus on business to consumer packaging rather than business to business packaging. The dairy and dairy-substitutes packaging studies covered in the meta-analysis are summarized in Table 4.

Table 4: Overview of LCA studies on dairy and dairy-substitutes packaging.

The option with the lowest impact on climate change shaded green.[*]

Environmental impact of biodegradable food packaging when considering food waste[**]
Dilkes-Hoffman et al. (2018)

The premise of this paper is that biodegradable plastic packaging has a role to play in replacing conventional multi-layer plastic packaging that is non-recyclable and non-degradable. One of the foods considered is cheese.

Functional unit: 1 kg of packaged product at the house

Geographic scope: Australia

Traditional packaging	Bio-based packaging	Main conclusions
PP wrap	Polyhydroxyalkanoate (PHA)-TPS wrap	The current end-of-life for food packaging and food waste in Australia is landfilling. Under these conditions, the PHA packaging performs worse overall compared to traditional PP packaging. Including food waste in the analysis does reduce the packaging contribution to overall impact, but not as much as for meat products as the global warming potential of cheese is less than for beef. Thus, **for the PHA wrap to outperform the PP wrap it would need to bring about a significant reduction in food waste.** The study concludes that a benefit of bio-based plastics is the opportunity to increase the amount of food waste available for biological processing.

Role of packaging in LCA of food products[***]
Silvenius et al. (2011)

This study investigates the environmental impacts of a variety of food product packaging types. Importantly, the study also includes the impacts associated with the food wasted. Consumer surveys are used to determine typical wastage rates at the household level for different types of packaging.

Functional unit: 1,000 kg of soygurt drink consumed

Geographic scope: Finland

Single portion	Bulk quantity	Main conclusions
150ml PP cup with aluminium lid	750ml liquid packaging board	For this food product, the effect of including food waste is not as pronounced as for meat, for example. This is because **the product has a high water-content and relatively low overall environmental impacts compared to the packaging**. For most waste management scenarios considered, the liquid packaging board had lower impacts for all levels of food wastage considered. Landfilling without energy recovery is the exception, where PP cups perform marginally better as both the liquid packaging board and food waste degrade to methane.

[*] Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

[**] The relatively few studies considering bio-based and biodegradable plastics led to the decision to include this study in the meta-analysis even though it does not fully meet the selection criteria (it considers only greenhouse gas emissions and water use).

[***] The fact that this study is the only one to include a consideration of household-level food waste led to the decision to include it in the meta-analysis despite it considering only carbon footprint.

Table 4: Continued – Overview of LCA studies on dairy and dairy-substitutes packaging.

The option with the lowest impact on climate change shaded green.*

Plastic or Glass: A New Environmental Assessment with a Marine Litter Indicator for the Comparison of Pasteurized Milk Bottles

Stefanini et al. (2021)

This LCA compares the environmental impacts of bottles made of PET, rPET, non-returnable glass and returnable glass.	**Functional unit:** Container for one litre of pasteurized milk **Geographic scope:** Italy

Plastic (PET)	Glass	Main conclusions
PET bottle	Non-returnable glass bottle	**The rPET bottle has the lowest impacts across all impact categories considered, followed by the PET bottle.** The glass bottle has the poorest performance across all indicators. After 8 uses, the returnable glass bottle has similar performance to the PET bottle. **When considering potential marine impact, the returnable glass bottle has the lowest impact, followed by rPET and PET, with the non-returnable glass bottle having the highest impact.**
rPET bottle	Returnable glass bottle	

The influence of packaging attributes on consumer behaviour in food packaging life cycle assessment studies – A neglected topic**

Wikström et al. (2014)

This study compares various types of traditional packaging for yoghurt to investigate the impact of food waste on overall environmental impact. The packaging types differ mainly in terms of the volume of yoghurt contained as well as the ability to obtain a portion easily.	**Functional unit:** 1 kg of eaten food **Geographic scope:** Developed country

Single portion	Bulk quantity	Main conclusions
PE, Aluminium and PP laminate pouch	900g PP and Aluminium tub	**If the packaging is recycled, then the small tubs are the preferred packaging type in terms of contribution to global warming** (the only indicator considered in this study). If incineration is the waste management option, then the large tub is preferable. **The impact of food waste is not overly significant for this food type as the impacts associated with the yoghurt are relatively small compared to the packaging impacts.** However, the single-portion 6-pack tubs are associated with less food wastage than the larger tub, which makes them the more attractive option when food waste is included. **The pouch has a high ratio of packaging material to product and is only favoured when the food waste is reduced by 15% compared to the other packaging options**
PS 6-pack tubs		

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* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

** The relatively few studies considering food waste led to the decision to include this study in the meta-analysis despite it considering only carbon footprint.

02 RESULTS FROM SUPERMARKET FOOD PACKAGING LIFE CYCLE ASSESSMENTS

The LCA studies included under dairy and dairy-substitutes packaging serve to highlight the complex interplay between packaging size, the overall material type and use, and food waste. Food sold in larger packaging sizes can in some cases lead to a lower overall environmental impacts compared to food sold in smaller portion sizes, due to reduced material usage. This was seen in the soygurt drink study of Silvenius *et al*. (2011). The converse is true in the yoghurt packaging study of Wikström *et al*. (2014), where the single-portion PS tubs outperform the larger 900g tub, although in this case the packaging types are closer in terms of weight. The single-portion pouch contains more packaging per product delivered and even though could be resealed and contains a single portion (thereby reducing food waste), the benefits of the avoided food waste are not sufficient to outweigh the impacts associated with the increased packaging. Unlike the meat packaging studies, where food waste is a determining factor in overall environmental performance, **for dairy and dairy substitutes the packaging weight, material type and level of food waste are all determining factors, with none of these more important than another universally.** This is because the impacts of food waste for this food type are comparable to the packaging impacts.

The LCA study on single-use and returnable packaging for fresh milk similarly highlights the importance of material type (milk losses are not considered in this study). The **single-use rPET bottle has the lowest impacts across all impacts considered** in the study **outperforming the returnable glass bottle**, even if the latter is used in excess of 20 times. This is because of its **high recycled content and the lightness of the material**. The returnable glass bottles do however, score best on the marine plastic indicator developed for the study (Stefanini *et al*. 2021).

End-of-life waste management is another factor that impacts on packaging preferences. Landfilling (without energy recovery) of bio-based plastics (Dilkes-Hoffman *et al*. 2018) and liquid packaging board (Wikström *et al*. 2014) together with food waste led to increased greenhouse gas emissions. Landfilling with energy recovery, recycling and incineration, typically resulted in lower GHG impacts for these products, but increased plastic packaging end-of-life impacts. It must be noted that the studies did not engage with the feasibility of separating food waste from the packaging to facilitate material recycling. Dilkes-Hoffman *et al*. (2018), however, note that bio-based plastics present an opportunity to co-dispose of food waste and packaging in a manner that reduces overall environmental impacts. An interesting observation for this particular food sub-category is that food waste emissions at end-of-life are lower if the food waste is treated with wastewater (i.e. disposed of down the drain) compared to disposed of in a landfill, where the anaerobic conditions break the organic matter down to release methane.

Recommendations for dairy and dairy-substitute packaging

- For food types, such as dairy and dairy substitutes, where the environmental impacts associated with food waste are comparable to the environmental impacts of the packaging, deeper investigation is required to understand the trade-offs in the country context taking into account consumer behaviour. This can be achieved through conducting specific LCA studies.
- Single-portion packaging is preferred over bulk packaging of a similar material, when the packaging weight to product ratio is comparable (i.e. single portions aren't over packaged) and where it results in reduced food wastage.
- Over-packaged single-portion packaging should be avoided unless it can be demonstrated that the impacts associated with the additional packaging are off-set by reduced food waste.

2.1.3 Packaging for refrigerated prepared foods

Only one study is included under this category, that deals with cheesecake sold in a single-use 2-count tray, wrapped in a film to provide a barrier to oxygen. The packaging options assessed in the study are broadly applicable to other **refrigerated prepared foods** sold in supermarkets, e.g. **sandwiches**. No other LCA studies were found in the literature that dealt with prepared foods intended for consumption in the home[9].

This study by Gutierrez, Meleddu and Piga (2017) confirms that **packaging that extends the shelf life of food products and avoids food waste has overall environmental benefits over traditional packaging.** The benefits arise from not only avoided food waste but also from lower transport requirements to deliver the same quantity of sold products. In this study, the extended shelf life packaging already had marginally lower environmental impacts compared to traditional PET packaging. In other cases, it is possible that the extended shelf life packaging may have higher burdens than conventional packaging and so investigation is required to ensure that the food waste reductions outweigh these additional packaging-related burdens.

Table 5: Overview of LCA study on refrigerated prepared food packaging.

The option with the lowest impact on climate change shaded green.*

Food losses, shelf life extension and environmental impact of a packaged cheesecake: A life cycle assessment
Gutierrez, Meleddu and Piga (2017)

This study investigates the trade-offs between packaging designed to extend shelf life of a cheesecake and food losses.

Functional unit: A tray containing two cheesecakes weighing 300 g (28 days)

Geographic scope: Italy

Traditional packaging	Extended shelf life packaging	Main conclusions
PET tray and PET film	EVOH/PS/PE tray, EVOH/ oriented PET (OPET)/PE film	When comparing the two packaging types, without considering shelf life effects, the PET has marginally higher environmental impacts. When the impact of shelf life extension is included in the analysis the benefits of the extended shelf life packaging is clear: less food wastage, lower packaging impact and lower distribution impacts as the supplier needs to make fewer trips to deliver the same quantity of sold cheesecakes.

* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

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[9] A separate meta-analysis is available on single-use takeaway food packaging and its alternatives, see https://www.lifecycleinitiative.org/library/single-use-plastic-take-away-food-packaging-and-its-alternatives/

02 RESULTS FROM SUPERMARKET FOOD PACKAGING LIFE CYCLE ASSESSMENTS

TYPES OF PACKAGING FOR FRESH PRODUCE COVERED IN THE LCA STUDIES

Packaging for ready-to-eat fresh fruits and vegetables

Plastic tub sealed with plastic film

Pillow bag (PP)

Supermarket packaging for whole fruits and vegetables

Plastic tray (PS)

Plastic bag (LDPE)

Clamshell (PET)

Plastic tray (OPS) and wrap

Plastic tray (PP or PLA)

Moulded pulp tray

Transit packaging for whole fruits and vegetables

Wooden crate

Plastic crate

Collapsible plastic crate

Cardboard box

Composite mango tray

LIFE CYCLE ASSESSMENTS OF PACKAGING FOR FRESH PRODUCE WHAT THE SCIENCE TELLS US

Preferred type of packaging for fresh produce depending on the context

The content of the matrix is simplified and aims to summarise the narrative of this section. Please refer to the full narrative of Section 2.2 for details.

	Willing consumer and conducive legislative context (consumers willing and able to change behaviour related to purchasing, returning and recycling packaging)		**Unwilling consumer and/or unfavorable legislative context** (consumers unwilling or not able to change behaviour related to purchasing, returning and recycling packaging)	
	POOR WASTE MANAGEMENT (landfill and open dumping; poor/no recycling or recovery)	**GOOD WASTE MANAGEMENT** (high recovery and recycling rates)	**POOR WASTE MANAGEMENT** (landfill and open dumping; poor/no recycling or recovery)	**GOOD WASTE MANAGEMENT** (high recovery and recycling rates)
Ready-to-eat and easily damaged fresh fruit and vegetables	**Minimize food waste** OR reduce packaging materials whichever results in greater benefits	**Minimize food waste** Packaging that extends shelf life AND Bio-based and biodegradable packaging to allow co-disposal of food waste with packaging	**Minimize food waste OR reduce packaging materials** whichever results in greater benefits	
Whole fruit and veg. incl. transit packaging	**Avoid packaging** Fruit and vegetables sold loose; transported in reusable plastic crates	**Avoid packaging** Fruit and vegetables sold loose; transported in reusable plastic crates or cardboard boxes with high recycled content	**Minimize packaging** plastic bag or, for soft/ easily damaged produce PS tray and wrap; transported in reusable plastic crates	**High recycled content packaging** Plastic bag, or high-recycled content tray and wrap; transported in reusable plastic crates or cardboard boxes with high recycled content

🟦 **Packaging should be minimized/avoided/reusable**

🟩 **Food waste and packaging material are both important factors**

* Product photography by Rothko Brand Partners and sourced online

2.2 PACKAGING FOR FRESH PRODUCE

For the purposes of this meta-analysis, packaging for fresh produce sold in supermarkets is broken down into the following three sub-sections:

- Ready-to-eat fresh fruit and vegetables that need specialized packaging, e.g. peeled and cut vegetables, washed lettuce leaves, herbs etc.;
- Fruit and vegetables that are sold whole, either packaged (in bags, containers or wrapped trays, e.g. tomatoes, berries, mushrooms etc.) or loose (where customers place the number of items they wish to purchase in a bag that is weighed in the store, e.g. potatoes, bananas, apples etc.)
- Transit packaging for fresh produce packaging systems.

This breakdown merely provides a way to organize the LCA studies found in the literature and it is recognised that how a particular fruit or vegetable is distributed will depend on the particular market and context, including such factors as the distance the produce needs to be transported and consumer preferences. Indeed, in most supermarkets it is possible to find both a packaged and unpackaged version of a particular fruit or vegetable, with the packaged version often available in more than one packaging format (e.g. box, bag and punnet). Furthermore, high value produce, such as berries, might be packaged in specialized packaging in some markets (especially if they have been transported long-distances) but sold loose or minimally packaged in others.

Transit packaging is found to strongly influence the environmental impacts of fresh produce packaging systems, often accounting for a higher share of the overall packaging impacts than the primary (consumer-facing) packaging. It has also been a particularly active area of LCA research, especially in the assessment of reusable versus single-use transit packaging options, and is therefore afforded its own sub-section in the meta-analysis.

2.2.1 Packaging for ready-to-eat fresh fruit and vegetables

All LCA studies considered on ready-to-eat fresh fruit and vegetables evaluate **single-use, business to consumer (B2C) packaging,** and no reusable packaging or returnable models are covered in the current LCA literature. The packaging can be manufactured from a variety of materials, including: PP, LDPE, HDPE, PET and PLA. The LCA studies on pre-cut fruit and lettuce covered in the meta-analysis demonstrate the growing interest in **active packaging** options that contain chemicals/nanoparticles embedded in the packaging **to extend the shelf life of the product.** The embedded chemicals act as antimicrobial compounds, oxygen/ethylene/moisture scavengers and/or antioxidant emitters, improving product protection and thereby reducing food waste. It should be noted, however, that the LCA studies do not take into account any potential human health risks associated with active packaging that have been raised. For example, the concern that the unintentional migration of compounds (some classified as biocides) into the product may result in contamination and potential impact on human health (Food Packaging Forum 2014). The LCA studies covered in the meta-analysis that consider packaging for ready-to-eat fresh fruit and vegetables are summarized in Table 6.

Table 6: Overview of LCA studies on ready-to-eat fresh fruits and vegetables packaging.

The option with the lowest impact on climate change shaded green.*

Evaluation of physiochemical/microbial properties and life cycle assessment (LCA) of PLA-based nanocovmposite active packaging

Lorite et al. (2017)

The aim of this study is to assess novel PLA-nanocomposites in comparison to conventional PET and PLA packaging for fresh-cut melons. The PLA-nanocomposite is designed to improve the protection of the cut melon.

Three PLA options are compared to PET in scenarios that look at improved shelf life (reduced food waste), and current and desired end-of-life treatment.

Functional unit: Packaging for 100,000 kg of fresh fruit

Geographic scope: Europe

Traditional packaging	Active packaging	Main conclusions
🟩 PET	PLA-nanocomposite (nonoclay) PLA-nanocomposite (nanoclay and surfactant) PLA-nanocomposite (nanowhiskers and surfactant)	**Fossil-fuel derived PET has lower impacts in the majority of impact categories** considered; primarily a result of high impacts linked with energy consumption for PLA production, although the bio-based nature of PLA results in lower human health impacts than PET. **The novel PLA-nanocomposites need to extend the shelf life by approximately 30% for the PLA options to match the environmental impacts of PET.** End-of-life management has relatively low impacts compared with material production; however, with desired waste management, PLA would have lower end-of-life impacts than PET.

Sustainability Analysis of Active Packaging for the Fresh Cut Vegetable Industry by Means of Attributional and Consequential Life Cycle Assessment

Vigil et al. (2020)

The aim of this study is to assess PP and PLA films coated with zinc oxide (ZnO) bactericidal nanoparticles in comparison to PP films for fresh-cut products. These options are assessed using both attributional and consequential LCA systems in order to ensure that the impacts of production, end-of-life and food waste are considered.**

Functional unit: Packaging for 130 g serving of fresh-cut lettuce eaten by the consumer (3.94 g of packaging film)

Geographic scope: Spain

Traditional packaging	Active packaging	Main conclusions
PP	ZnO coated PP 🟩 ZnO coated PLA	Fossil-fuel derived PET has lower impacts in the majority of impact categories considered; primarily a result of high impacts linked with energy consumption for PLA production, although the bio-based nature of PLA results in lower human health impacts than PET. The novel PLA-nanocomposites need to extend the shelf life by approximately 30% for the PLA options to match the environmental impacts of PET. End-of-life management has relatively low impacts compared with material production; however, with desired waste management, PLA would have lower end-of-life impacts than PET.

* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

** In order to allow a first assessment of the significance of marine plastic litter impacts relative to existing life cycle impacts, the results of this study are extended to include the potential physical effects on biota caused by the exposure of organisms to microplastic marine litter. See Section 3.4 and Appendix C for details]

When food waste, and the resultant increase in agricultural production required to meet consumers food demand, is considered, as in Vigil *et al*. (2020); it is clear that **agricultural production of the packaged products dominates impacts. Any packaging that decreases food waste** therefore results in decreased environmental impacts.

Active packaging has been shown to have potential to extend shelf life and decrease food wastage (Lorite *et al*. 2017; Vigil *et al*. 2020), including through maintaining the appearance of food for longer. However, active packaging does not allow for reusable and/or returnable packaging, as the compounds are utilized during use, but it can still be recycled or industrially composted at end-of-life.

Recommendations for packaging for ready-to-eat fresh fruit and vegetables

- Packaging for ready-to-eat fresh fruit and vegetables should be designed to extend shelf life and reduce food waste, as agricultural production of the packaged product is the key source of impacts.
- Active packaging options should be further investigated and developed, as they have the potential to significantly improve shelf life and reduce food waste; whilst ensuring their safety and addressing concerns of potential impacts on human health.
- Any alternative packaging should be assessed across its value chain (i.e. with LCA), taking into account actual end-of-life treatment in the particular context in which it will be used, so as not to overstate recycling or composting benefits.

High angle shot of fresh raspberries in a plastic box on a white surface. (Freepik)

2.2.2 Packaging for whole fruit and vegetables

This section covers LCA studies that analyse the supply of whole fruits and vegetables available in supermarkets loose and packaged. When sold loose, customers typically pay by weight and can use either a store-supplied plastic produce bag for their purchases or bring their own reusable bags. The whole fruit and vegetable packaging covered in the meta-analysis include plastic bags, plastic "clamshells" and "tray and wrap" type packaging. In the latter, the tray can be made from a number of different materials (different types of plastic, cardboard, moulded pulp etc.) with typically a plastic film overwrap. The LCA studies covered in the meta-analysis summarized in Table 7.

Table 7: Overview of LCA studies on whole fruit and vegetable packaging.

The option with the lowest impact on climate change shaded green.*

Comparative Life Cycle Assessment Report of Food Packaging Products
Belley (2011)

The aim of this LCA is to compare different types of materials for fruit and vegetable trays sold in Quebec. **Functional unit:** Contain and permit the stacking and retailing of the amount of fruits or vegetables that can be contained in a tray volume of 52 cubic inches to consumer in Québec in 2010	**Geographic scope:** Quebec, Canada

Traditional packaging	Bio-based packaging	Main conclusions
🟩 100% virgin extruded polystyrene foam (XPS)	90% virgin-10% recycled polylactide (PLA)	The **XPS and moulded pulp trays were found to be strongly preferred across all impact categories**. This is a consequence of the much lighter weight of the XPS tray relative to the other plastic trays, and that the moulded pulp tray is made from recycled materials. This follows from the finding that the life cycle environmental impacts of all the trays are strongly dominated by the production of raw materials and energy use in manufacturing (forming). The PLA tray has the highest potential impacts across the greatest number of impact categories.
90% virgin-10% recycled oriented polystyrene (OPS)	90% virgin-10% recycled PP	
90% virgin-10% recycled PET (rPET)	🟩 100% recycled moulded pulp	
100% recycled PET (rPET)		

Evaluating the Environmental Impacts of Packaging Fresh Tomatoes Using Life-Cycle Thinking and Assessment**
Stevenson et al. (2010)

The aim of this study was to evaluate both the direct environmental impacts of packaging options for fresh tomatoes, and the impact of tomato packaging decisions on the environmental impacts of the packaged product.	**Functional unit:** 100 lbs (45.4 kg) of tomatoes delivered to the supermarket **Geographic scope:** USA

Traditional packaging	Sold loose	Main conclusions
EPS tray wrapped in a PE film; transported in corrugated cardboard box	🟩 "Loose" tomatoes transported in a corrugated cardboard box with a GPPS liner; PE produce bag	**Tomatoes sold loose have the same or lower environmental impacts than tomatoes sold in a PS tray and wrap.** Tomatoes sold in a PET clamshell have the highest impacts, although the differences between the three options are slight. When 2% losses are assumed for the loose tomatoes, the PS tray and wrap is the preferred option by a slight margin, although the PET clamshell remains the least preferred.
PET clamshell; transported in corrugated cardboard box		

* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

** The relatively few studies on whole fruit and vegetable packaging, especially those that consider losses, led to the decision to include this study in the meta-analysis, even though it does not fully meet the selection criteria (it is more than 10 years old and was not peer reviewed).

Table 7: Continued – Overview of LCA studies on whole fruit and vegetable packaging.

The option with the lowest impact on climate change shaded green.*

Packaging Waste Prevention in the Distribution of Fruit and Vegetables: An Assessment Based on the Life Cycle Perspective

Tua et al. (2017)

This LCA is carried out to determine the environmental effectiveness of supplying locally grown fruit and vegetables direct to customers inside a returnable crate (the so-called “box scheme”) over the traditional large-scale retail of fruit and vegetables, either loose or packaged.

Functional unit: The distribution of 1 kg of product (i.e. carrots or apples)

Geographic scope: Italy

Traditional packaging	Box scheme	Main conclusions
LDPE polybag	Returnable PP crate, drop-off point delivery	For both **carrots and apples**, customers **purchasing loose products at large retail stores has the lowest impacts**. The box scheme with home delivery had similar impacts to the other traditional packaging types, whilst the box scheme with drop-off point delivery was the least preferred. The poor performance of the box scheme is largely a result of single-use crates/boxes used in the transport of produce from farm to distribution hub. If this were changed to reusable plastic crates (as in the traditional distribution network for produce sold loose) then the box scheme with home delivery would become the best option for carrots and equal to the loose purchase option for apples.
Tray and PVC stretch film (Carrots: PP tray; Apples: PS tray)	Returnable PP crate, home delivery	
🟩 Loose with HDPE purchasing bag		

* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

The environmental impacts of the **packaging and transport of fresh fruit and vegetables** can be **surprisingly large** relative to the environmental impacts of growing and storing them (US EPA 2010; Boschiero *et al.* 2019). Transport and packaging together are found to contribute around 75% of the potential life cycle climate change impact of fresh tomatoes in the USA, with packaging contributing 15-20% of that (depending on the type of packaging) (US EPA 2010). Packaging is found to be the highest contributor to both the climate change impact and cumulative energy demand of the post-harvest life of apples in Italy (Boschiero *et al.* 2019).

Purchasing loose (or minimally packaged) fruit and vegetables has lower environmental impacts than purchasing produce packed in single-use plastic bags, trays or clamshells (US EPA 2010; Tua *et al.* 2017; WRAP 2022). When looking at the most common ways **apples and carrots** are packaged and distributed to large retail stores in Italy, Tua *et al.* (2017) found that distribution in reusable plastic crates, with reusable plastic nesting trays (in the case of apples), had the lowest environmental impacts. The apples and carrots are displayed in the same crates in the retail store, thereby avoiding the need for additional display packaging. However, a customer typically takes a plastic bag to hold their loose produce. Tua *et al*’s study showed that produce sold packaged in polybags can have the same (or better) environmental performance than the loose option when a customer purchasing loose only partially fills their bag.

Stevenson *et al.* (2010) found that **tomatoes** sold loose (i.e. transported in cardboard boxes with General Purpose Polystyrene (GPPS) liners) are environmentally preferred to tomatoes packed in a PS tray or in a PET clamshell. However, when the authors’ assumed that packaging would reduce tomato spoilage by 2%, tomatoes packed in the PS tray and wrap had a slightly lower impact on climate change than tomatoes sold loose (although a 2% reduction in spoilage was not enough to offset the greenhouse gas emissions associated with producing PET clamshells).

Whilst spoilage is an important consideration when comparing minimally packaged and packaged whole fresh produce, a recent WRAP report disputes that packaging necessarily decreases losses. In fact, WRAP’s analysis finds that **packaging increases food waste, largely as a result of consumers buying more than they actually end up eating** (i.e. that **whilst retail losses might decrease, losses at home can actually increase**). If all apples, bananas and potatoes were sold loose in the UK, 60,000 tonnes of food waste and 8,800 tonnes of plastic packaging could be avoided per year (WRAP 2022).

In their evaluation of the **materials from which fruit and vegetable trays can be made**, Belley (2011) found a **strong preference for XPS and moulded pulp trays**. This is due to the light weight (less material) that goes into the XPS trays relative to the other plastic trays (and since production of raw materials is a high contributor to the environmental performance of the plastic trays). Whilst the good environmental performance of the moulded pulp trays is a result of them being made from recycled materials (and the material incurring only the impacts associated with collecting and pulping newspapers). For the same reason, the **rPET trays show better environmental performance** than the other plastic trays without high recycled contents. The PLA tray is the least environmentally preferred, partly because it is the heaviest of the trays after the PET tray (i.e. more material leads to more impacts associated with producing the material), and partly because of the high ecosystem impacts associated with growing the corn from which the PLA is made (arising primarily from the large land areas requiring cultivation). A PS tray was also found to be environmentally preferred to a PET clamshell in the packaging of fresh tomatoes (US EPA 2010).

Recommendations for packaging for whole fruit and vegetables

- Whole fruit and vegetables should be sold loose (unless it can be shown that packaging reduces overall food waste).
- When purchasing loose, customers should be encouraged to bring their own reusable bags in which to weigh their produce.
- In packaged whole fresh produce, a plastic bag has lower impacts than a tray and wrap.
- For whole fruit and vegetables packaged in single-use trays, include as high recycled content as possible as this reduces the environmental impacts of the tray (recognising that this needs to be done within the constraints of food safety regulations, as in many countries legislation restricts recycled content in food-contact packaging[10]). Safety and efficacy of trays with high recycled content will thus need to be ensured (and proven), with changes in legislation, where necessary, to support rather than restrict recycled content in food packaging.
- Innovation and policy support are needed to move fruit and vegetable trays – that are currently single-use and mostly not recycled – to become reusable and/or recyclable. In instances where the use of trays is unavoidable, e.g. soft or small fruit, returnable packaging models, such as those discussed in Section 3.3, have potential to considerably reduce the environmental impacts of packaged fruit and vegetables.

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[10] Matthews *et al*. (2021) provide a review of this issue in the context of the European Union's strategy for plastics in a circular economy, and the European Commission recently adopted new rules to facilitate the processes around the development, certification, and use of recycled plastic in food contact materials (European Commission 2022).

2.2.2 Transit packaging for fresh produce (fruit and vegetables, bread)

The section covers the transit packaging for fresh produce, i.e. the crates and boxes in which loose or packaged produce is transported to supermarkets. In loose purchasing systems, produce is displayed in store in the same crates/boxes or packed out into bins. For lightly packaged products, e.g. those in plastic bags, the transit packaging can have a higher contribution to environmental impacts than the primary (consumer-facing) packaging. Transit packaging is also an important aspect on which to focus since **business-to-business packaging offers greater potential for reusable packaging options than business-to-consumer packaging.** The LCAs covered in the meta-analysis of fresh produce transit packaging are summarized in Table 8.

Table 8: Overview of LCA studies on transit packaging for fresh produce.

The option with the lowest impact on climate change shaded green.*

When Plastic Packaging Should Be Preferred: Life Cycle Analysis of Packages for Fruit and Vegetable Distribution in the Spanish Peninsular Market
Abejón et al. (2020)

The aim of this LCA is to obtain objective information on the environmental impact associated with the distribution of fruits and vegetables in the domestic Spanish (peninsular) market. Reusable plastic crates and single-use cardboard boxes are compared.**	**Functional unit:** Distribution of 6,666,700 packages full of fruits and vegetables, with a transported weight of 15 kg, in single-use cardboard boxes or reusable plastic crates (conservative scenario) **Geographic scope:** Spain

Single-use	Reusable	Main conclusions
Corrugated cardboard box	Collapsible plastic crate (HDPE/PP)	The **reusable plastic crates** are found to **have significantly lower environmental impacts** and energy consumption than the single-use cardboard boxes. This is true across all impact categories. Furthermore, sensitivity analyses showed the preference for plastic crates over cardboard boxes to be robust. Only at high (hypothetical) levels of recycled content in the boxes, they were found to have lower impacts than the plastic crates in some impacts.

* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B

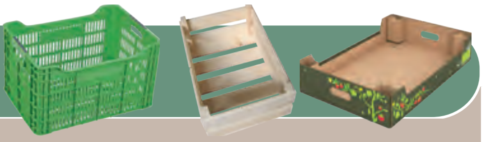
** In order to allow a first assessment of the significance of marine plastic litter impacts relative to existing life cycle impacts, the results of this study are extended to include the potential physical effects on biota caused by the exposure of organisms to microplastic marine litter. See Section 3.4 and Appendix C for details

Table 8: Continued – Overview of LCA studies on transit packaging for fresh produce.

The option with the lowest impact on climate change shaded green.*

An Extended Life Cycle Analysis of Packaging Systems for Fruit and Vegetable Transport in Europe

Albrecht et al. (2013)



This LCA compares the most common European fruit and vegetable transport packaging systems, namely single-use wood and cardboard boxes, and reusable plastic crates, considering their environmental, economic and social impacts.	**Functional unit:** Distribution of 15 kg of fruits/ vegetables in 3,333,350 filled boxes/crates (number of boxes/crates to transport 1,000 tonnes of goods five times a year) **Geographic scope:** Europe (Spain, Italy, France, the Netherlands, Germany and Great Britain)

Single-use	Reusable	Main conclusions
Corrugated cardboard box	Plastic crate (HDPE/PP) (5 fillings per year over a lifetime of 10 years)	**Plastic crates and wooden boxes have lower impacts than cardboard boxes** for fruit and vegetable transport in Europe, with the **plastic crates having the lowest impacts overall**. The lower impacts of plastic and wooden crates relative to cardboard boxes are across all impact indicators included in the study, whilst the plastic and wooden crates have similar impacts with respect to global warming and acidification potential. The high impacts of the cardboard boxes arise mainly because of the high-quality cardboard required for the transport of fruit and vegetables.
Wood crate		

Comparative Lifecycle Assessment of Mango Packaging Made from a Polyethylene/ Natural Fiber-Composite and from Cardboard Material

Bernstad Saraiva et al. (2016)

This LCA compares the use of traditional cardboard boxes for the transport of mangos with a composite packaging designed specifically for reusability and for the reduction of mango losses. Two scenarios are explored – a local market and transport to end-consumers in Europe.	**Functional unit:** Transport of ten mangos per packaging from the area of production to the end-consumer **Geographic scope:** Brazil, with waste management in Brazil and Europe

Single-use	Reusable	Main conclusions
Cardboard box	Recycled HDPE frame with a High Impact polystyrene (HIPS) tray	If the packaging is used only once, the cardboard box scores the lowest across all impact indicators other than ozone depletion potential. The 100% recycled HDPE frame is the least preferred, with environmental preference for the composite frame increasing with increasing percentage of natural fibres. **The composite frame with 30% fibres has to be reused four times on the local market for it to break even with the cardboard box** (in terms of its climate change impact), and reused 35 times if transported to Europe.
	Composite frame (recycled HDPE reinforced with natural fibres) with a HIPS tray (lowest climate impact if reused more than four times locally or 29 times for export)	

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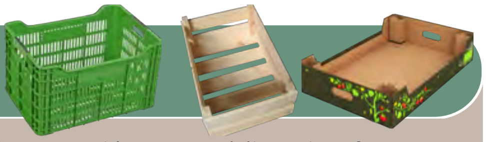
* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

Table 8: Continued – Overview of LCA studies on transit packaging for fresh produce.

The option with the lowest impact on climate change shaded green.*

Sustainable Packaging: An Evaluation of Crates for Food through a Life Cycle Approach

Del Borghi et al. (2021)



This LCA compares the environmental impacts of single-use vs. reusable crates made of different materials.

Functional unit: 1 crate with an external dimension of 400 x 600 x 240 mm and an inner volume of 50 l.

Geographic scope: Italy

Single-use	Reusable	Main conclusions
Plastic crate (HDPE/PP)	🟩 Plastic crate (HDPE/PP), used 50 times	**Reusable plastic crates are strongly preferred** across all environmental indicators considered, compared to all the single-use options. Among the single-use crates, solid wood crates have the best environmental performance and plastic crates the worst.
Corrugated cardboard box		
Solid wood crate		
Medium Density Fibreboard (MDF) crate		
Particle board crate		

Reusable Plastic Crate or Recyclable Cardboard Box? A Comparison of Two Delivery Systems.

Koskela et al. (2014)

The aim of this study is to compare the life cycle environmental impacts of a real bread delivery system using either reusable plastic crates or recyclable corrugated cardboard boxes for product transportation.

Functional unit: Eight loaves of bread delivered in one crate/box

Geographic scope: Finland

Single-use	Reusable	Main conclusions
🟩 Corrugated cardboard box	Plastic crate (HDPE)	The **recyclable cardboard box** is found to have **lower impacts than the reusable HPDE plastic crate** across all impact categories considered. Transportation is found to play a very important role in the environmental impacts, demonstrating the importance of the weights of products and transport distances in determining environmental preference between cardboard boxes and reusable plastic crates.

* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

Table 8: Continued – Overview of LCA studies on transit packaging for fresh produce.

The option with the lowest impact on climate change shaded green.*

A Comparative Life Cycle Assessment of Disposable and Reusable Packaging for the Distribution of Italian Fruit and Vegetables

Levi et al. (2011)

The aim of this study is to suggest design solutions to make the distribution of 12 types of fruit and vegetables sustainable. Single-use corrugated boxes and reusable plastic containers of various sizes are considered.	**Functional unit:** 100 kg of fruits and vegetables available at the large-scale retail outlets in Italy and in Europe **Geographic scope:** Italy, Europe

Single-use	Reusable	Main conclusions
Corrugated cardboard box	Plastic crate (PP)	The **reusable plastic crate** system **is** environmentally **preferred when transport distances are less than 1,200 km**. At distances higher than this, the corrugated cardboard box has the lower environmental impacts. The number of uses is important for the plastic crate system, but after 20 uses, increasing the uses further has little effect on impacts. For the boxes, where the material production has a higher contribution to life cycle impacts than in the plastic crates, **bigger boxes result in lower impacts**.

Life Cycle Assessment of Reusable Plastic Crates (RPCs)

Tua et al. (2019)

The aim of this LCA is to assess the life cycle environmental performance of reusable plastic crates as a function of the number of deliveries, with a special focus on the reconditioning stage, as well as to compare reusable plastic crates with single-use plastic crates.	**Functional unit:** 1,200 kg (corresponding to 100 RPCs) of carrying capacity at each delivery **Geographic scope:** Italy

Single-use	Reusable	Main conclusions
Lightweight single-use plastic crate (PP)	Collapsible reusable plastic crate (PP)	The **reusable plastic crate** system **has lower environmental impacts than single-use plastic crates** (across all environmental indicators) after just three uses. The reuse/reconditioning stage starts to dominate the life cycle impacts of reusable plastic crates after about 20 uses (before that the production stage accounts for the main share of impacts). Within the reconditioning stage, transport of crates from users to the reconditioning plant account for the main share of impacts, followed by the electricity consumption of the reconditioning plant.

* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

The distribution of fruit and vegetables in reusable plastic crates is found to be environmentally preferred (Albrecht *et al.* 2013; Tua *et al.* 2017, 2019; Abejón *et al.* 2020; Del Borghi *et al.* 2021) to distribution in single-use cardboard boxes, although there are **contexts in which this is not necessarily the case** (Levi *et al*. 2011; Koskela *et al*. 2014). Abejón *et al*. (2020) found that the use of **collapsible reusable plastic crates** has lowest environmental impacts, and lower energy and water consumption across a range of study configurations (e.g. different recycled contents, recycling rates, breakage rates, number of uses etc.). The analysis of Abejón *et al*. (2020) is however, for fruit and vegetables distribution in local markets (the Spanish peninsular market). For the distribution of bread across the whole of Finland, Koskela *at al*. (2014) found distribution in **corrugated cardboard boxes** to be environmentally preferred to distribution in reusable plastic crates. In the Finnish case study, transportation was found to be the highest contributor to environmental impacts by a considerable margin. This high contribution to life cycle impacts from transportation was confirmed by Levi *et al*. (2011), who found that **cardboard boxes** were environmentally preferred for the distribution of fruit and vegetables at distances over 1,200 km. At distances less than this, a reusable plastic crate system was shown to be preferred.

It is clear from the transit packaging LCA studies reviewed that the **transport distance is critical when considering reusable transit packaging** (local versus national delivery) and that optimizing the return of crates to minimize transport emissions, e.g. by making plastic crates collapsible, is necessary for reusable transit packaging to be preferred. Along with the transport distance, the **number of reuses of plastic crates** is highly influential in determining their impacts. This is especially important at the lower end, since the production and disposal impacts are divided by the number of uses, i.e. halved for two uses, divided by three for three uses etc., but becomes less important as the number of uses increases. The effect of the number of uses (i.e. the decrease in impacts with each successive use), was found by Levi *et al*. (2011) to fall drastically after 20, and be insignificant after 50.

Among the single-use transit packaging options, Del Borghi *et al*. (2021) found that **solid wood crates** have the best environmental performance and single-use plastic crates the worst.

Albrecht *et al.* (2013) similarly find single-use wood crates to be preferred to cardboard boxes[11]. **High recycled content in the cardboard boxes**, and **high recycling rates** at end-of-life **considerably improve the relative performance of cardboard boxes relative to reusable plastic crates**. The variation in the relative environmental performance of cardboard boxes across the LCA studies arises not only from differing assumptions of recycling rates and recycled content, but also from differences in how the studies model end-of-life management. Methods that incorporate the benefits of recycling into the system (such as in system expansion, whereby the cardboard box system is credited for avoided virgin pulp) lead to far lower impacts than methods that capture only the avoided waste disposal. Whilst most of the studies reviewed applied system expansion/avoided burdens to model end-of-life, whether open-loop or closed-loop recycling was applied had a strong influence on the impacts of the cardboard system. In studies applying closed-loop recycling, the cardboard box system was only credited for the virgin pulp avoided in the production of cardboard boxes used in the packaging system (this is relatively low at around 15% because of the need for high-quality cardboard in the distribution of fruit and vegetables (Albrecht *et al.* 2013)). This is in contrast to studies applying open-loop recycling, in which up to 100% of the avoided virgin pulp from recycling boxes is credited to the cardboard box system. Such differences point to **the need for standardisation of methods** in the assessment of packaging systems.

Recommendations for transit packaging

- Promote the use of reusable collapsible plastic crates for the transport of fruit and vegetables in local markets.
- In reusable crate systems, encourage decentralized distribution systems (washing and reconditioning plants) to minimize transport emissions and allow these to operate over larger markets.
- In single-use boxes and crates, include as high recycled content (secondary material) as possible within the material quality restrictions of the crate/box.

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[11] The finding of Albrecht *et al. (2013) that cardboard boxes are the least preferred, and of Del Borghi et al. (2021) that cardboard boxes are the 2*nd-least preferred (after single-use plastic crates) appears contradictory to Levi *et al.* (2011) and Koskela *et al.* (2014) that find cardboard boxes to be the best option (even compared to reusable plastic crates, which are the best performing option in Albrecht *et al.* and Del Borghi *et al.*). However, obtaining a coherent ranking of options across the studies is not possible since the studies do not consider a consistent set of options (e.g. Levi *et al.* and Koskela *et al.* do not consider any other single-use options), do not have a consistent set of parameters (most notably transport distance, which is shown to be influential in determining whether a returnable system is preferred or not) and do not apply consistent modelling choices (most notably recycling credits for waste cardboard, which vary widely between the studies).

Image: Plastic crates stacked on top of each other. (Romain Huneau, Unsplash.com)

02 RESULTS FROM SUPERMARKET FOOD PACKAGING LIFE CYCLE ASSESSMENTS

TYPES OF PACKAGING FOR PANTRY GOODS COVERED IN THE LCA STUDIES

Single-use glass bottle
Plastic bottle (PET)
Plastic bottle (PET) with shrink sleeve
Plastic bottle (HDPE)
Aseptic carton (liquid packaging board)
Multi-layer pouch (doypack)
Glass jar

Steel can
Plastic wrap (PP)
Aluminium foil and kraft paper
Aluminium foil and cardboard
Steel can with aluminium pull-tab
Plastic cup (PP)
Laminate pouch
Returnable glass jar

Pillow bag (PP)
Plastic bag in cardboard box
Plastic bag in cardboard box
Plastic bag (LDPE)
Mixed plastic bag
Gravity bin dispenser (for loose purchase of dry goods)

LIFE CYCLE ASSESSMENTS OF PACKAGING FOR PANTRY GOODS: WHAT THE SCIENCE TELLS US

Preferred type of packaging for shelf stable and dry goods depending on context

The content of the matrix is simplified and aims to summarise the narrative of this section. Please refer to the full narrative of Section 2.3 for details.

	Willing consumer and conducive legislative context (consumers willing and able to change behaviour related to purchasing, returning and recycling packaging)		**Unwilling consumer and/or unfavorable legislative context** (consumers unwilling or not able to change behaviour related to purchasing, returning and recycling packaging)	
	POOR WASTE MANAGEMENT (landfill and open dumping; poor/no recycling or recovery)	**GOOD WASTE MANAGEMENT** (high recovery and recycling rates)	**POOR WASTE MANAGEMENT** (landfill and open dumping; poor/no recycling or recovery)	**GOOD WASTE MANAGEMENT** (high recovery and recycling rates)
Shelf-stable	**Returnable packaging**	**Returnable packaging** if returns are high and logistics optimized OR High recycled content packaging	**Minimize packaging** minimize materials and weight, e.g. plastic rather than glass or cardboard	**High recycled content packaging** that is itself recyclable
Dry goods	**Avoid packaging** (product sold loose) provided bulk transport of product is material-efficient (e.g. reusable plastic crates)	**Avoid packaging** (product sold loose) provided bulk transport of product is material-efficient, e.g. reusable plastic crates or cardboard boxes with high recycled content	**Minimize packaging** minimize materials and weight. Avoid double packaging (e.g. bag in a box)	**High recycled content packaging** that is itself recyclable, e.g. cardboard carton

🟩 **Packaging should be minimized/avoided/reusable**

* Product photography by Rothko Brand Partners and sourced online

2.3 PACKAGING FOR PANTRY GOODS (SHELF STABLE AND DRY GOODS)

This section covers LCA studies on shelf-stable food products, i.e. products that do not require refrigeration (at least not until they are opened) and are able to be stored in the home for a number of weeks/months.

This food packaging archetype covers a wide range of food products in a diversity of packaging types/materials, including glass bottles/jars, metal cans, plastic pouches, and cartons. LCAs on this packaging archetype, so far tend to focus on material substitutions, with just two studies looking at returnable/reusable alternatives.

In this meta-analysis we consider two sets of pantry goods:

- **Shelf-stable goods** such as olive oil, extended shelf life milk, olives, chocolate, tuna, honey and tofu; and
- **Dry goods**, such as cereals, rice, pulses, pasta etc., for which alternative "packaging-free" or "loose" distribution models could be more easily implemented.

2.3.1 Packaging for shelf-stable goods

The LCAs included in the meta-analysis on shelf-stable food products cover a range of food product types and packaging options. The LCAs are summarized in Table 9. The analysis also draws on the wider LCA literature, in particular, on review studies that look at packaging material-types more broadly (i.e. without focusing on a particular food product).

Table 9: Overview of LCA studies on packaging of shelf-stable food products.

The option with the lowest impact on climate change shaded green.*

Glass vs. Plastic: Life Cycle Assessment of Extra-Virgin Olive Oil (EVOO) Bottles across Global Supply Chains.
Accorsi, Versari and Manzini (2015)

This study explores the environmental impacts of a global supply chain for extra-virgin olive oil, with a focus on packaging decisions.

Functional unit: 1 litre bottle of Extra Virgin Olive Oil (EVOO)

Geographic scope: Bottling in Italy with distribution worldwide

Single-use plastic	Single-use glass	Main conclusions
PET bottle	🟩 Glass bottle	At recycling rates above 40% olive oil in a glass bottle has a lower climate impact than olive oil in a PET bottle. This is despite olive oil in glass bottles having higher impacts than olive oil in PET up until packaging end-of-life. **If a recycled content of 50% was possible** (currently not the case in Italy) then **the rPET bottle would be the environmentally preferred option**.
rPET bottle		

Comparative Life Cycle Assessment of Packaging Systems for Extended Shelf Life Milk
Bertolini et al. (2016)

This LCA is a comparative analysis of the environmental impacts of different packaging systems used for extended shelf life milk.

Functional unit: One litre of extended shelf life (ESL) milk with a guaranteed shelf life of 30 days

Geographic scope: Italy

Single-use plastic	Single-use carton	Main conclusions
HDPE bottle	🟩 Multi-layer carton	The environmental impacts of ESL milk in **multi-layer cartons** are, on average, more than 12% lower than that in HDPE bottles and more than 34% lower than that in PET bottles with shrink sleeve labels.
PET bottle with shrink sleeve		

* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

Table 9: Continued – Overview of LCA studies on packaging of shelf-stable food products.

The option with the lowest impact on climate change shaded green.*

Exploring the Environmental Impacts of Olive Packaging Solutions for the European Food Market

Bertoluci, Leroy and Olsson (2014)

The aim of this study is to compare the environmental performance an olive packaging system across five different European countries, as well as to assess the influence of consumer preference and behaviours on packaging performance.		**Functional unit:** Packaging of one tonne of olives for aperitif and cooking usage **Geographic scope:** France, Germany, Italy, Spain and Sweden
Single-use plastic	Single-use non-plastic	Main conclusions
Doypack (multi-layered plastic stand-up pouch)	Glass jar	The **multi-layered plastic stand-up pouch (doypack) has the lowest impacts** across all five countries The glass jar has the highest impacts despite its high rate of recycling in the five countries. **The energy mix in the country is influential** in the glass jars' high impacts. Only in Sweden, where the energy mix is 50% nuclear, does the steel can have higher impacts than the glass jar in some impact categories. Although the plastic pouch scored best on the life cycle impact indicators, it was shown to be least preferred in a functional analysis, associated with increased food loss and non-recyclable; indicating a trade-off between life cycle environmental indicators and other aspects of packaging performance.
	Steel can	

Environmental Analysis along the Supply Chain of Dark, Milk and White Chocolate: A Life Cycle Comparison

Bianchi et al. (2021)

This LCA assesses the environmental impacts of dark, milk and white chocolate, including an assessment of three packaging materials.		**Functional unit:** 1 kg of chocolate **Geographic scope:** Italy
Single-use plastic	Single-use fibre-based and foil	Main conclusions
PP wrapper	Aluminium foil and kraft paper	By far the main source of environmental impacts is the chocolate raw materials, in particular the dairy and cocoa derivatives. The **plastic wrapper is the best packaging option** by a considerable margin, with impacts less than half those of the foil and paper or foil and cardboard across all eight impact categories considered.
	Aluminium foil and cardboard	

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* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

Table 9: Continued – Overview of LCA studies on packaging of shelf-stable food products.

The option with the lowest impact on climate change shaded green.*

Comparative Carbon Footprint of Packaging Systems for Tuna Products**

Poovarodom, Ponnak and Manatphrom (2012)

The aim of this study is to evaluate and compare the carbon footprint associated with canned tuna meat, with a focus on single-serving packaging systems.

Functional unit: Commercially available unit package designed for one single serving

Geographic scope: Thailand, with consumption in the UK

Single-use metal	Single-use plastic	Main conclusions
Chrome-coated steel can, with an aluminium pull ring tab	Retort pouch (PP, aluminium foil and orientated nylon)	The overall carbon footprint of **canned tuna in retort cups** is 10% and 22% less than when packaged in metal cans and retort pouches, respectively. **Packaging** and its associated processing **constitute a significant fraction of the life cycle carbon footprint of a single serving of tuna**, ranging from 20% to 40%.
	🟩 Retort cup (PP and ethylene vinyl alcohol (EVOH))	

Reuse of Honey Jars for Healthier Bees: Developing a Sustainable Honey Jars Supply Chain through the Use of LCA.

Postacchini et al. (2018)

This study aims to improve the sustainability of an existing honey production supply chain by evaluating the potential for changing from the current single-use glass jar system to a returnable glass jar system.

Functional unit: The packaging of 300 metric tonnes of honey a year, over a time period of 5 years

Geographic scope: Italy

Single-use	Returnable	Main conclusions
Single-use glass jar	🟩 Reusable glass jar	The study found that with an optimized reverse logistics supply chain (i.e. a logistics centre for collecting and distributing jars in each municipality and a washing/packaging centre at the honey consortium's headquarters), **the change to returnable glass jars could reduce environmental impacts by more than 70%** (on average) over five years. These high reductions in impacts are possible when assuming 85% of jars are returned. However, the returnable glass jars still showed environmental preference to single-use jars even if only 10% of jars are returned.

* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

** This study is included in the meta-analysis even though it does not fully meet the selection criteria (it considers only climate change impact) because of the very few studies from a developing country context.

Table 9: Continued – Overview of LCA studies on packaging of shelf-stable food products.

The option with the lowest impact on climate change shaded green.*

Analyzing the Packaging Strategy of Packaging-Free Supermarkets
Scharpenberg et al. (2021)

The goal of this LCA is to clarify the environmental advantages of packaging-free supermarkets. In so doing, the authors conduct a comparative LCA of six products retailed at the German packaging-free supermarket Original Unverpackt (OU) relative to conventionally packaged products sold in small organic food stores. The products assessed are chia seeds, fruit bears, noodles, **tofu**, dishwashing shower gel and detergent.

Functional unit: Quantity of packaging material needed to transport and provide one unit of the conventionally packaged product, and one unit of the "packaging-free" product in its typical container size.

Geographic scope: Germany

Single-use	Returnable	Main conclusions
Tofu in plastic bags	🟩 Tofu in returnable glasses	Selling tofu in returnable glasses did not show any environmental benefits relative to tofu sold in conventional plastic packaging. The **higher greenhouse gas emissions of the glass packaging result especially from transport** (the small local supplier transports the tofu product to store in a passenger car), as well as from the production of the glass (due to the relatively low return rate of glasses).

* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

LCAs tend to show that for shelf-stable goods, **single-use plastic packaging has lower impacts than other traditional single-use packaging materials** (Poovarodom, Ponnak, and Manatphrom 2012; Franklin Associates 2018; Almeida *et al.* 2021; Bianchi *et al.* 2021). This is largely a result of the light weight of plastic packaging. Even though the impacts per kg of plastic packaging may sometimes be higher than impacts per kg of the alternative packaging material, significantly more kilograms of the alternative material are required to perform the same function. In a high-level theoretical substitution analysis of packaging on the North American market, Franklin Associates (2018) calculated that the impacts of plastic packaging are between 2% (eutrophication potential) and 59% (global warming potential) of those of the available substitutes (steel, aluminium, glass, paper-based packaging etc.). Over the entire packaging sector, substituting plastics with other packaging materials currently used on the North American market was estimated to double the greenhouse gas emissions (GHG) from the packaging sector[12]. The better performance of plastic packaging was seen across all but one of the packaging sectors (caps and closures), with the degree to which plastic packaging performed better varying widely between the sectors. For example, substitutes perform very poorly when it comes to replacing plastic stretch and shrink films (4.7 times higher GHG emissions), but less poorly when it comes to heavier packaging, such as bottles and rigid packaging (1.6–1.9 times higher GHG emissions).

Indeed, the better performance of plastic packaging is not seen in all markets. **In the packaging of liquid foods, single-use cartons seem to have lower climate change impacts than single-use plastic and glass.** Geographical context is important as the degree of recycled content in the carton board, and the recycling rate of cartons at end-of-life are instrumental in their lower impacts. In studies commissioned by Tetra Pak, in European and Nordic markets, cartons are shown to be environmentally preferred across most environmental impacts, other than "use of nature" (because of the high land use in forestry) (Schlecht and Wellenreuther 2020). A similar result was found on the Australian and New Zealand markets, where cartons have lower or similar impacts to plastic pouches and rPET bottles (with glass and virgin PET bottles having considerably higher impacts) (Warmerdam and Vickers 2021). Another common finding is that **smaller packaging formats have higher emissions** since they require more material per volume of product.

Although relatively few LCAs are available on shelf-stable

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[12] GWP of substitutes are 1.7 times higher than plastic in a scenario with no decomposition in landfill and 2.2 times higher in a scenario with maximum decomposition in landfill (for the USA) (Franklin Associates 2018)

food packaging, LCAs on beverage packaging systems are much more plentiful (Zero Waste Europe 2020). Many of the findings from these studies are relevant also for food packaging since many shelf-stable foods are packaged in bottles, e.g. tomato sauce, oil, soup, pasta sauce etc. In an analysis of bottle LCAs, **single-use glass bottles seem to have the highest overall impacts compared to other alternative materials**, such as PET bottles, aluminium cans and cartons (UNEP 2020b; Zero Waste Europe 2020; Stefanini *et al*. 2021), despite glass jars being functionally preferred by consumers (Bertoluci, Leroy, and Olsson 2014). An exception here was a study on olive oil, which found glass bottles to have lower impacts than PET bottles, as a consequence of the higher recycling rate (and recycled content) of glass bottles over PET bottles (noting that this result would reverse if recycled content and recycling rates of PET were able to increase) (Accorsi, Versari, and Manzini 2015). **In packaging of seafood products, steel and aluminium cans show as the least environmentally preferred, compared to plastic packaging options** (Poovarodom, Ponnak, and Manatphrom 2012; Almeida *et al*. 2021).

LCA studies show that when it comes to **reusable packaging options, reusable glass bottles are always preferred to single-use glass bottles** (UNEP 2020b; Zero Waste Europe 2020; Stefanini *et al*. 2021), even after as little as two uses, with a similar finding for returnable glass jars in Italy (Postacchini *et al*. 2018). A returnable glass jar system with an optimized reuse supply chain was found to have lower climate and ecosystem impacts than a single-use jar system even when only 10% of the glass jars were assumed returned (Postacchini *et al*. 2018). On the other hand, the selling of tofu in returnable glass jars was found to show no environmental benefits, when the returnable glass system was compared to tofu sold in plastic bags (Scharpenberg *et al*. 2021). Even a high return rate of the glass packaging was not sufficient to significantly change the results of the comparison, because much of the impact of the returnable glass system arises in the transport of the glass packaging between the producer and the retail store[13].

Reusable glass bottles are found to be environmentally preferred to single-use PET bottles (UNEP 2020b; Zero Waste Europe 2020) **or have similar/indistinguishable performance**, i.e. to have better performance in some environmental categories and poorer performance in others (Stefanini *et al*. 2021).

LCA studies provide conflicting results in comparisons between reusable glass bottles and aluminium cans, and between reusable glass bottles and single-use beverage cartons; **aluminium cans and beverage cartons tend to have lower life cycle emissions, but reusable glass bottles can have comparable or lower emissions if transport distances are low and the number of reuses is high** (UNEP 2020b; Zero Waste Europe 2020).

Recommendations for packaging for shelf-stable goods

- Glass packaging should be avoided unless reusable.
- Packaging, especially single-use, should be made from materials generating high-quality secondary materials at end-of-life, which will lead to strong recycling markets for waste packaging materials.
- Flexible packaging and films represent a particular challenge in that they are often the packaging option with the lowest potential climate impact but are simultaneously the packaging option with the most problematic end-of-life. They are mostly not recycled and are the most likely to be littered (easily wind-borne). Furthermore, there are few viable, lower-impact alternatives to single-use plastic films available. Further research and support for innovative packaging materials are needed.
- Returnable packaging systems should be supported and incentivized (see Section 3.3), but the packaging system must first be carefully assessed with LCA to ensure environmental benefits. This should include a consideration of distances travelled over the service life (i.e. from use to collection, cleaning, maintenance and redistribution), number of use cycles, packaging weight, and choice of materials, including the recycled content and recyclability of the material.

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[13] It is worth noting that this case study involved a small supplier using a passenger car, and different results might be obtained if the returnable packaging were part of a more optimized logistics system.

2.3.2 Packaging for dry goods (rice, pasta, cereals, seeds, nuts etc.)

This section looks at a particular sub-set of pantry/shelf stable food products, that of dry goods. The two LCAs on dry goods covered in the meta-analysis are particularly chosen as they cover alternative distribution models in addition to traditionally packaged options. In these distribution models (**refill by bulk dispenser),** consumer-facing packaging is eliminated and customers dispense only the amount of product they wish to purchase into their own reusable container or into a bag provided by the store. The LCAs covered in the meta-analysis of dry goods are summarized in Table 10.

Table 10: Overview of LCA studies with alternatives to traditionally packaged dry goods.

The option with the lowest impact on climate change shaded green.*

Life Cycle Assessment of Waste Prevention in the Delivery of Pasta, Breakfast Cereals, and Rice
Dolci et al. (2016)

In this study the most common single-use packaging solutions for dry pasta, breakfast cereals and rice in Italy are compared with distributing the produce loose (bulk refill dispenser)

Functional unit: 1 kg of food product (dry pasta, breakfast cereals or rice)

Geographic scope: Italy

Traditional packaging	Product sold loose (dispensed)	Main conclusions
Dry pasta: PP pillow bag	Dispensed dry pasta, LDPE purchase bag	Whether or not distributing produce loose is environmentally preferred depends on the food type and particularly on the single-use packaging used for the food product. **Distributing cereals and rice loose was shown to have lower impacts than the comparative single-use packaging when this included cardboard**. However, where the product is packed only in a plastic bag, distributing the product loose not only shows no environmental benefits but can even increase impacts and waste generation.
Rice: Mixed plastic bag inside cartonboard box	Dispensed rice, LDPE purchase bag	
Breakfast cereal: HDPE bag inside a cartonboard box	Dispensed cereal, LDPE purchase bag	

* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

The option with the lowest impact on climate change shaded green.*

Image: Various pasta in transparent plastic bags. (Tatiana Atamaniuk, iStockphoto.com)

Table 9: Continued – Overview of LCA studies with alternatives to traditionally packaged dry goods.

The option with the lowest impact on climate change shaded green.*

Analyzing the Packaging Strategy of Packaging-Free Supermarkets

Scharpenberg et al. (2021)

The goal of this LCA was to clarify the environmental advantages of packaging-free supermarkets. In so doing, the authors conduct a comparative LCA of six products retailed at the German packaging-free supermarket Original Unverpackt (OU) relative to conventionally packaged products sold in small organic food stores. The products assessed are chia seeds, fruit bears, noodles, tofu, dishwashing shower gel and detergent.

Functional unit: Quantity of packaging material needed to transport and provide one unit of the conventionally packaged product, and one unit of the "packaging-free" product in its typical container size.

Geographic scope: Germany

Traditional packaging	Product sold loose (dispensed)	Main conclusions
Chia seeds in single-use LDPE bag	Chia seeds dispensed from bulk dispenser into customer's own reusable container	The **environmental benefits of the bulk refill dispenser system over conventional packaging depend on the food product**, as well as on the conventional packaging against which it is being compared. **Environmental benefits were observed for "packaging-free" chia seeds and noodles, but not for fruit bears.** The dispensed fruit bears do not show the environmental advantages of the other products because the sticky fruit bears place additional cleaning requirements on the dispensers (i.e. additional use of energy and water in the cleaning process).
Noodles in PP bag	Noodles from bulk dispenser (own reusable container)	
Fruit bears in mixed plastic bags	Fruit bears from bulk dispenser (own reusable container)	

* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

Rice and pasta packed in plastic bags are found to have consistently lower environmental impacts than rice and pasta packed in cartonboard boxes. This is largely a consequence of the greater weight of cardboard relative to plastic, with the cartonboard boxes found to have five times the mass of packaging per kg dry pasta distributed than PP pillow bags. The cartonboard box was also shown to be the major contributor to the bag-in-box packaging of breakfast cereals, accounting for around 75% of cereal packaging's life cycle impacts.

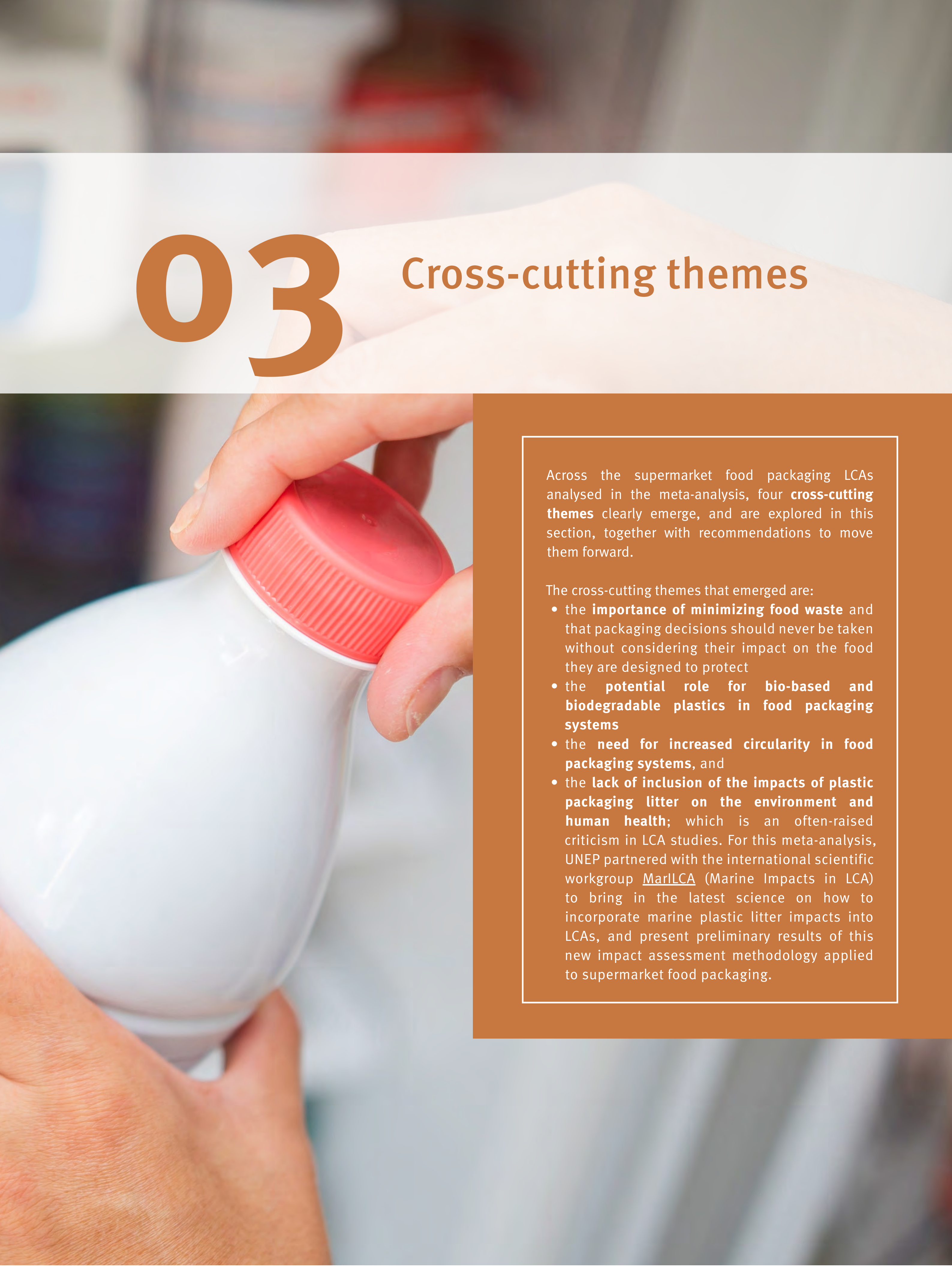
Simpler packaging (bag only without a box) and larger pack sizes are environmentally preferred in the packaging of **breakfast cereals and rice** (Dolci et al. 2016). The smaller the bag-in-box pack size, the greater the packaging mass per kg of product distributed, and thus the greater the environmental impacts. It is however important to note that food waste was not considered in the study, with both less protective packaging and larger pack sizes having the potential to increase food waste (and thus environmental impacts).

Bulk refill dispensing of dry goods (also called loose distribution or "packaging-free") is a potential solution for reducing the packaging and therefore the environmental impacts of dry foods, such as cereals, rice, dry pasta, nuts, dried fruit, candy etc. In a bulk dispensing system, the food product is transported to the store in bulk packaging and placed in a gravity bin dispenser. Consumers are able to dispense the amount of product they wish to purchase from the dispensers at the retail store. **Whether or not bulk dispensing is environmentally preferred depends on the food type and on the single-use packaging replaced by dispensing.** For example, Dolci et al. (2016) found that replacing bag-in-box type single-use packaging, e.g. as commonly used for breakfast cereals, by bulk dispensing can reduce impacts by between 39 and 83%. On the other hand, where the dry food product is packed only in a plastic bag, e.g. dry pasta, replacing the single-use packaging system with a bulk dispensing system not only shows no environmental benefits but can even increase impacts and waste generation (when customers use an additional bag for dispensing product into). Similarly, Scharpenberg et al. (2021) found environmental benefits in bulk dispensing of chia seeds and noodles, but that bulk dispensing of fruit bears increased impacts relative to conventionally packaged fruit bears (due to the increased need to clean the dispensers with the sticky fruit bears). In general, **bulk refill dispensing decreases packaging impacts when the bulk refill dispensing system replaces a cartonboard box** (Dolci et al. 2016) **or when the dispensers do not require substantial cleaning** (Scharpenberg et al. 2021).

Potential savings in food waste due to customers being able to purchase only the amount of product they require was not evaluated in these studies. In Dolci *et al*. (2016) the potential for customers to reuse bags or bring their own containers when purchasing loose product is not evaluated, although this is included in Scharpenberg (2021), albeit with the conservative assumption that containers are washed after every use. **If food waste and more accurate modelling of consumer behaviour with regards to reusable containers were included, the benefits of bulk refill dispensing over traditionally packaged dry food products may well be higher than indicated by these studies.**

Recommendations for packaging for dry goods

- Packaging should be simplified wherever this can be done without increasing food waste, i.e. avoiding "bag-in-box" types packaging.
- Larger and more material efficient packaging sizes should be encouraged, wherever this will not cause an increase in food waste.
- Distributing product loose / bulk refill dispensing of rice, pasta etc. should target heavily packaged products (e.g. breakfast cereals) and not those where the dispensing system replaces just a plastic bag, especially if customers do not use a reusable container for their purchase (i.e. when customers dispense product into a single-use plastic bag for their purchase). Furthermore, product suitability for bulk refill dispensing should be based on potential for transport/bulk packaging to be reusable and for not requiring frequent or in-depth cleaning of dispensers.



03

Cross-cutting themes

Across the supermarket food packaging LCAs analysed in the meta-analysis, four **cross-cutting themes** clearly emerge, and are explored in this section, together with recommendations to move them forward.

The cross-cutting themes that emerged are:

- the **importance of minimizing food waste** and that packaging decisions should never be taken without considering their impact on the food they are designed to protect
- the **potential role for bio-based and biodegradable plastics in food packaging systems**
- the **need for increased circularity in food packaging systems**, and
- the **lack of inclusion of the impacts of plastic packaging litter on the environment and human health**; which is an often-raised criticism in LCA studies. For this meta-analysis, UNEP partnered with the international scientific workgroup MarILCA (Marine Impacts in LCA) to bring in the latest science on how to incorporate marine plastic litter impacts into LCAs, and present preliminary results of this new impact assessment methodology applied to supermarket food packaging.

Image: Milk in a plastic bottle. (andreswd, iStockphoto.com)

03 CROSS-CUTTING THEMES

3.1 FOOD WASTE VS. PACKAGING IMPACTS

Food waste is a significant issue. Almost 24% of food is wasted along the value chain, with 8% of this wastage occurring in households (Searchinger *et al*. 2019). See Figure 4. The amount of food waste varies by region (Figure 5), with a large proportion of food loss happening in developed regions, mostly at the household level. Developing regions, show a lower share of total food wasted than developed regions, but a much larger portion of this food loss happens at production and at handling and storage stages. Although many factors influence food waste by consumers (WRAP 2022), the packaging does have a key role to play. **When seeking solutions to single-use plastic food packaging it is important not to exacerbate the food waste problem.**

Figure 4: Estimate of global food waste along the food supply chain. Source: Searchinger *et al*. (2019)

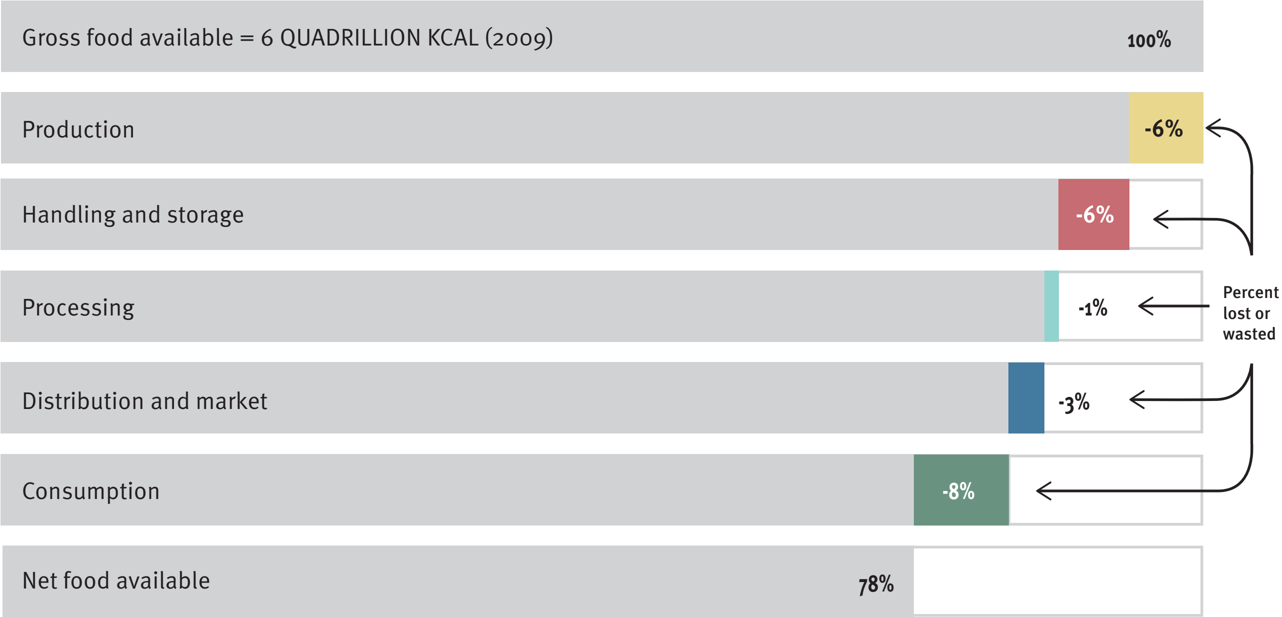
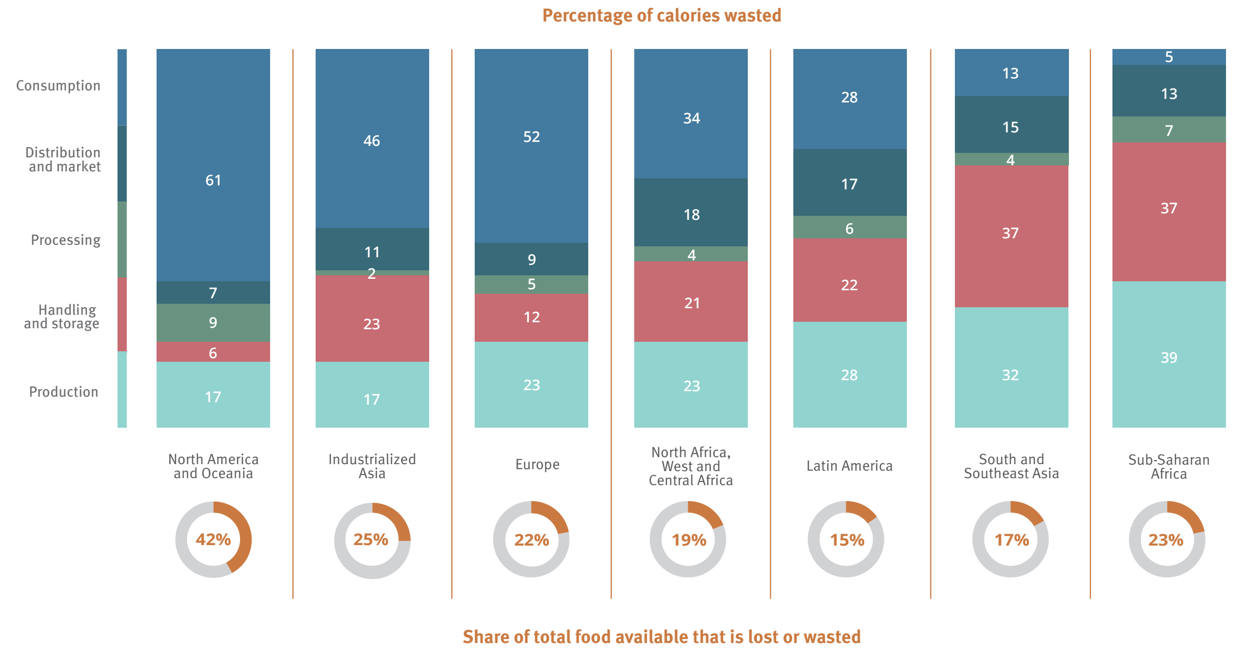


Figure 5: Food loss along the value chain, by region and life cycle stage. Source: Searchinger *et al*. (2019)



While food packaging can reduce the amount of food waste generated at retailers and at households, trade-offs exist as packaging also gives rise to environmental impacts. In many of the studies included in this meta-analysis, modified atmosphere packaging, designed specifically to extend shelf life of refrigerated products and minimize food waste, has higher packaging impacts compared to conventional packaging. However, on balance when including avoided food waste, the modified packaging has greater overall environmental benefits. The relative contribution of packaging to overall environmental impact differs depending on the food type and the packaging commonly used. **For different foods, the contribution of packaging to the overall environmental impact differs; in some cases, making up a significant proportion of total impact and in other cases being negligible compared to the environmental impacts associated with the food itself.** Licciardello (2017) terms this the **Packaging Relative Environmental Impact (PREI),** which is a useful framing to understand the importance of packaging in unpacking environmental burdens (see Box 1).

Box 1: The Packaging Relative Environmental Impact (PREI) for various foods (Licciardello 2017)

HIGH PREI FOODS

Foods with high PREI are foods where the choice of **packaging highly** influences the overall **environmental impact**, irrespective of the impact of the food itself. Packaging is often substantial. These include for instance beverages including carbonated cooldrinks, wine and beer, which are typically packaged in glass or aluminium cans, and other tinned foods or foods in glass jars.

LOW PREI FOODS

Foods with low PREI are foods with high environmental impacts for their production and for which the choice of packaging should be to **minimize the possibility of food ending up as waste.** Packaging for these foods has a small impact on their overall environmental impact relative to the food itself. This category includes for instance meat, coffee, freshly squeezed juices and butter.

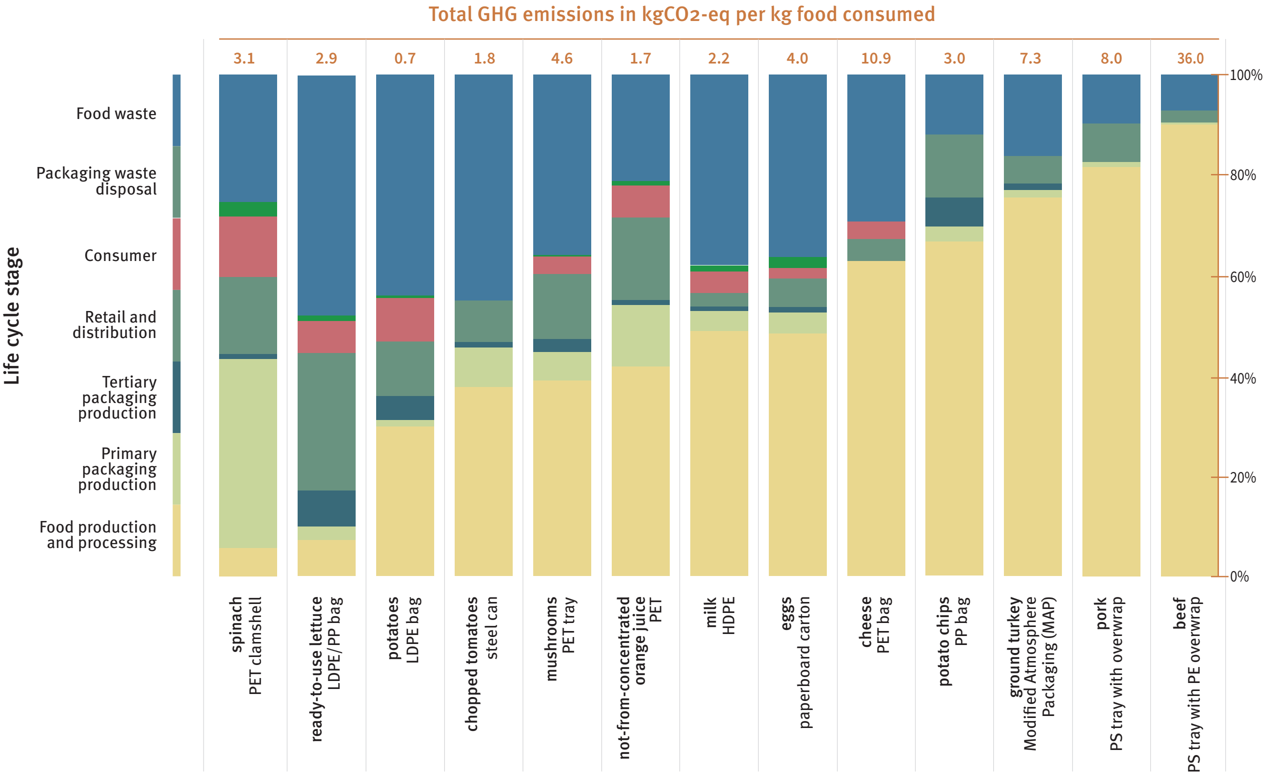
INTERMEDIATE PREI FOODS

Foods with intermediate PREI are foods with moderate environmental impacts for their production as well as their packaging. Often there is a trade-off between waste and packaging impacts. These categories includes breakfast cereals, pasta and yogurt.

The relative environmental impact of food (packaging and food waste) is demonstrated by Heller, Selke and Keoleian (2019). Figure 6 shows the **GHG emissions intensity for several food types** ranging from vegetables on the left of the diagram to beef on the right. This diagram clearly shows the wide range of GHG emissions intensity (including packaging) for different food products, from **0.7 kg CO_2eq per kg of potatoes consumed to 36 kg CO2eq per kg of beef consumed**.

The contribution of food consumed, food waste, packaging and other life cycle stages (i.e., distribution, retail, refrigeration, etc.) to overall emissions also differs according to food type. Food-related emissions (shown in Figure 6 as the bottom light blue segment for food production and processing and top dark blue segment for edible food waste contribution) are greater for foods with high GHG emissions intensity, such as beef and lower for vegetables.

Figure 6: Distribution of GHG emissions across life cycle stages for various foods and packaging combinations. Adapted from: Heller, Selke, and Keoleian (2019)



Recommendations

Any policies on packaging should consider the particular type of food to be packaged, since the environmental impacts of, respectively, food waste and packaging varies with food type. The following are broad recommendations, noting that detailed LCAs are needed to confirm these findings for specific cases:

- For foods associated with **high environmental impacts for their production** (foods with low PREI e.g. meat) packaging design should prioritize minimization of food waste.

- For foods with production-related environmental impacts **comparable** to packaging-related environmental impacts (e.g. dairy products), LCAs should determine the preferred packaging option. At low food wastage rates, the packaging tends to dominate the overall environmental profile, while at higher food wastage rates, the packaging is less important.

- For foods with **low environmental burdens in their production** (food with high PREI), packaging should be minimized/eliminated or reusable, wherever feasible.

3.2 BIO-BASED AND BIODEGRADABLE PLASTICS: DO THEY HAVE A ROLE TO PLAY IN FOOD PACKAGING?

Bio-based and biodegradable plastics are often put forward as a solution to the fossil-dependence and persistence in the environment of conventional plastics, and have been particularly suggested as suitable for food packaging (Peelman *et al.* 2013). Understanding bio-based plastics first requires an understanding of the difference between bio-sourced and biodegradable since the term "bio-plastics" can be assumed to mean either or both of these (see Table 11 for definitions of key terms around bio-based plastics).

This section brings together the findings of LCAs that consider bio-based and biodegradable plastic alternatives for meat and, fruit and vegetable packaging, as well as of three case studies that looked at bio-based and biodegradable food packaging more broadly (i.e. that do not specify a particular food product). The seven LCA studies informing this section are listed in Table 12.

Table 11: What are "bio-plastics"? Terms and definitions (UNEP 2021a)

Term	Definition
	Bio-plastics Plastics made from polymers that are either bio-sourced, biodegradable or both. For this reason, the term "bio-plastic" should never stand alone and it is necessary to specify, each time this word is used, the plastic's origin (bio-based or not) and end-of-life (biodegradable or not).
	Bio-based / bio-sourced plastics Plastics made from polymers derived from renewable resources (plants or animals). The sources of raw materials can vary and can include everything related to biomass and organic matter, in particular starches, sugars and vegetable oils. The polymers can be directly synthesized by plants or animals such as polysaccharides (starch, cellulose, chitosan, etc.), proteins (collagen, gelatin, casein, etc.) and lignins, or synthesized from biological resources such as vegetable oils (rape, soybean, sunflower, etc.). Other biopolymers, such as PHA, are produced by microorganisms through fermentation from sugars and starch.
	Biodegradable A material that can be decomposed under the action of microorganisms such as bacteria, fungi, algae or earthworms. To be truly meaningful, the term must be linked to the end products, to a timescale that is compatible with a human scale, and to the conditions of biodegradation (temperature, humidity, pH, and the quantity and nature of microorganism present). Typical end products are water, carbon dioxide and/or methane, energy and by-products (residues, new biomass).
	Biodegradable plastics Plastics made from polymers that are biodegradable under specified environmental conditions and above a specified degradation time as per accepted industry standards. Accepted industry standard specifications include, but are not limited to: ASTM D6400, ASTM D6868, ISO 17088 and EN 13432. **Most biodegradable plastics do not breakdown in the natural environment** but only under the controlled conditions found in industrial composting facilities (see Figure 15).
	Compostable A material that biodegrades under controlled conditions in the presence of oxygen. Composting results in a stabilized fertilizing material, rich in humid compounds, called compost. It is accompanied by the release of heat and carbon dioxide. It is a process widely used, especially in agricultural environments, because compost helps amend soil by improving its structure and fertility.
	Compostable plastics Plastics made from polymers capable of being biodegraded at elevated temperatures in soil under specified conditions and time scales, usually only encountered in an industrial composter. For industrial composting, standards apply: ISO 17088, EN 13432, ASTM 6400. This is in contrast to domestic or home composting.

Table 12: LCA studies considering bio-based plastics as alternatives to conventional plastic food packaging

Food archetype	LCA study	Summarized in:
Meat	• Dilkes-Hoffman *et al.* (2018) Environmental impact of biodegradable food packaging when considering food waste • Maga, Hiebel, and Aryan (2019) A comparative life cycle assessment of meat trays made of various packaging materials	Table 3
Fruit and vegetables: fresh cut and lettuce	• Vigil *et al.* (2020) Sustainability analysis of active packaging for the fresh cut vegetable industry by means of attributional & consequential life cycle assessment • Lorite *et al.* (2017) Evaluation of physiochemical/microbial properties and life cycle assessment (LCA) of PLA-based nanocomposite active packaging	Table 6
Fruit and vegetables: whole	• Belley and Samson (2011) Comparative life cycle assessment report of food packaging products: Final assessment report	Table 7
Food product not stated	• Bishop, Styles, and Lens (2021) Environmental performance of bioplastic packaging on fresh food produce: A consequential life cycle assessment • Suwanmanee *et al.* (2012) Life cycle assessment of single use thermoform boxes made from polystyrene (PS), polylactic acid, (PLA), and PLA/starch: Cradle to consumer gate • Hottle, Bilec and Landis (2017) Biopolymer production and end of life comparisons using life cycle assessment • Hermann, Blok and Patel (2010) Twisting biomaterials around your little finger: environmental impacts of bio-based wrappings	Table 13

Table 13: Overview of LCA studies on bio-based and biodegradable plastics.

The option with the lowest impact on climate change shaded green.*

Environmental performance of bioplastic packaging on fresh food produce: A consequential life cycle assessment
Bishop, Styles and Lens (2021)

This consequential LCA study focuses on the displacement on a large scale of plastic food packaging derived from fossil fuels with bio-based food packaging. The opportunities that this displacement would give rise to in terms of co-disposal of food waste and packaging is explored through several forward-looking end-of-life scenarios. These scenarios include a mix of incineration, composting, anaerobic digestion, recycling and the production of insect feed.

Functional unit: 1 tonne of fresh fruit and vegetable waste generated from UK households and associated food packaging of 51.12kg

Geographic scope: UK

Traditional	Bio-based and biodegradable	Main conclusions
“Average” fossil-based plastic (19% PP, 19% LDPE, 31% HDPE, 31% PET)	PLA (20% collected for industrial composting and anaerobic digestion)	Overall performance of PLA varied depending on the end-of-life options considered, with **the production of insect feed from PLA resulting in the lowest impacts**. Even for this best-case scenario, traditional fossil fuel-based plastic had lower impacts in 5 of the 16 environmental impact categories considered. When considering more “traditional” end-of-life scenarios, PLA only had lower impacts in 6-8 of the 16 categories, even when 80% of the waste is collected for industrial composting/anaerobic digestion or 100% is sent to anaerobic digestion. High impacts for PLA are linked primarily to maize feedstock production.
	PLA (40% collected)	
	PLA (60% collected)	
	PLA (80% collected)	
	PLA (100% to anaerobic digestion)	
	PLA (100% to industrial composting)	
	PLA (100% to incineration)	
	PLA (100% to insect feed)	

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* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

Table 13: Continued – Overview of LCA studies on bio-based and biodegradable plastics.

The option with the lowest impact on climate change shaded green.*

Twisting biomaterials around your little finger: environmental impacts of bio-based wrappings**
Hermann, Blok, and Patel (2010)

The aim of this study is to assess the environmental sustainability of bio-based printed packaging films in comparison to conventional, fossil fuel-based printed packaging films used for snack packaging. As such, the study compares cradle-to-grave environmental impacts of film **snack packages** manufactured from the 29 film combinations.

Functional unit: 1 m^2 of film

Geographic scope: Europe

Inner pack	Outer pack	Main conclusions
OPP/PE/MOPP	PE	**Bio-based*** plastic films and films manufactured partly from bio-based materials can have the same or lower impacts than fossil fuel-derived films**; however, numerous bio-based plastic film options have significantly increased impacts compared to the reference films. For inner packs, the traditional OPP film, as well as laminated Paper / OPP film, have the lowest impacts. For outer packs, bio-PE, Paper / EVA and Paper / BBP films have the lowest impacts.
OPP/PE/MOPP	Bio-PE (thicker film)	
Paper/PE/MOPP	Bio-PE	
Cellulose/PE/MOPP	OPP	
PLA/PE/MOPP	PLA	
MPLA/PLA/PLA		
PLA/AlO_x PLA	Cellulose	
PLA/AlO_x PLA	Cellulose (thicker film)	
PLA/SiO_x PLA	Paper/OPP	
SiO_x PLA/ SiO_x PLA	Paper/PLA	
MPLA/MPLA	Paper/PLA (thicker film)	
Paper/SiO_x PLA/PLA	Paper/PE	
Paper/Al/PLA	Paper/bio-based polyester (BBP)	
Paper/MPET/PP (peelable)	Paper/BBP (thicker film)	
Paper/MPET/PE (peelable)	Bio-PE (thinnest film, no adhesive)	
	Paper/EVA	
	Paper/BBP	

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* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

** This study is included in the meta-analysis even though it does not fully meet the selection criteria (it is from 2010) because very few studies looking at snack packaging were found in the literature.

*** Whilst all the bio-based wrappings considered in the study are made using biomaterials not all are biodegradable, e.g. PLA, cellulose and bio-based polyester (BBP) are biodegradable, whilst Bio-LDPE and Bio-HDPE are not.

Table 13: Continued – Overview of LCA studies on bio-based and biodegradable plastics.

The option with the lowest impact on climate change shaded green.*

Biopolymer production and end of life comparisons utilising life cycle assessment**
Hottle, Bilec, and Landis (2017)

The aim of this study is to assess the environmental sustainability of bio-based plastics in comparison to fossil fuel-derived plastics, while also considering end-of-life disposal methods.

Functional unit:1 kg of plastic

Geographic scope: USA

Traditional	Bio-based	Main conclusions
PET landfilled	PLA landfilled	**Non-biodegradable bio-based plastics** (Bio-LDPE, Bio-HDPE and Bio-PET) **have higher impacts than their fossil fuel-derived counterparts in most impact categories, with the exception of global warming and fossil fuel depletion**. The bio-based and biodegradable plastics (TPS and PLA) similarly have good relative environmental performance in some categories (notably human health and ecotoxicity), but worse performance in others. Composting has some advantages, especially when compared to impacts associated with landfilling, but **recycling provides the greatest benefits at end-of-life** (when offset credits are attributed to the plastics).
PET recycled	PLA composted	
HDPE landfilled	TPS landfilled	
HDPE recycled	TPS composted	
LDPE landfilled	Bio-PET landfilled	
LDPE recycled	Bio-PET recycled	
	Bio-HDPE landfilled	
	🟩 Bio-HDPE recycled	
	Bio-LDPE landfilled	
	🟩 Bio-LDPE recycled	

Life cycle assessment of single use thermoform boxes made from polystyrene (PS), polylactic acid (PLA), and PLA/starch: Cradle to consumer gate
Suwanmanee et al. (2013)

The aim of this study is to assess the environmental sustainability of bio-based and biodegradable plastics options to replace PS boxes in Thailand. The study covers only box production and does not include end-of-life disposal.

Functional unit: 10,000 thermo-formed trays, with a capacity of 100 g

Geographic scope: Thailand

Traditional	Bio-based and biodegradable	Main conclusions
🟩 PS	PLA	Across all impact categories and scenarios, **fossil fuel-derived PS has the lowest impacts**. This is due to the high impacts of corn and cassava production and energy consumption in the PLA production process.
	70% PLA; 30% starch	

* Climate change is the only indicator applied across all the studies considered in the meta-analysis. It is also often – but not always – indicative of trends in other environmental impacts. Providing the lowest climate change option in this table is not meant to imply that packaging systems should be evaluated on climate change impacts alone. The full set of indicators applied in each study can be found in the summary tables in Appendix B.

** This study is included in the meta-analysis even though it does not fully meet the selection criteria (it does not cover the full life cycle) because relatively few studies from developing countries were found in the literature.

The environmental benefits of substituting fossil fuel-derived plastics with bio-based plastics in food packaging are not clear cut, as across all studies the bio-based alternatives **reduce some impacts but increase others**. This is true for both bio-based and biodegradable plastics, such as PLA and TPS, and bio-based and non-biodegradable plastics, such as Bio-PE. While substituting bio-based plastics for fossil fuel-derived plastics reduces fossil energy consumption, there is a burden shift, with studies finding that bio-based plastics have higher impacts in other categories (Hottle, Bilec, and Landis 2017; Vendries *et al*. 2018; Maga, Hiebel, and Aryan 2019). The higher impacts are a consequence of the agricultural production of feedstocks, which require land, water and agrichemical inputs, along with energy inputs that are typically fossil fuel derived (Suwanmanee *et al*. 2013; Hottle, Bilec, and Landis 2017; Vendries *et al*. 2018; Maga, Hiebel, and Aryan 2019). Bio-based plastics produced with agricultural wastes as the feedstock are therefore a better alternative as they have lower impacts in these categories (Vigil *et al*. 2020).

Bio-based alternatives are sometimes, but not always, shown to have lower impacts on climate change. The PLA packaging option is shown to have the lowest carbon footprint (along with lowered impacts in other categories) in Bishop, Styles and Lens (2021) and Vigil *et al*. (2020). However, the good environmental performance of PLA in Bishop, Styles and Lens (2021) relies on PLA being used to produce insect feed at end-of-life, with environmental credits for offsetting the production of traditional animal protein feeds (fishmeal and soybean meal). The Vigil *et al*. study assumes that PLA is produced from maize starch produced as a waste product of agriculture, and is therefore assigned no impacts from the production of maize. In both Bishop, Styles and Lens (2021) and Lorite *et al*. (2017), the maize feedstock has significant environmental impacts and is the chief source of environmental impacts associated with PLA packaging.

A review of 25 published LCA studies, covering 50 bio-based polymers (both biodegradable and non-biodegradable) and 39 fossil fuel-based polymers, was not able to substantiate the prevailing scientific consensus that bio-based polymers have lower climate impacts than fossil-based polymers, finding them to have very similar ranges in energy use and GWP (Walker and Rothman 2020). It is especially **important that LCA studies on bio-based plastic packaging cover the whole life cycle,** as bio-based and biodegradable plastic packaging sent to landfill will degrade and release methane, which, if not captured, leads to higher greenhouse gas emissions for the bio-based plastic (Suwanmanee *et al*. 2013; Hottle, Bilec, and Landis 2017; Dilkes-Hoffman *et al*. 2018; Vendries *et al*. 2018). Whilst the ability of bio-based non-biodegradable plastics to be recycled at end-of-life is influential in their good performance with respect to climate change (when they are credited for avoiding the production of virgin plastic) (Hottle, Bilec, and Landis 2017; Vendries *et al*. 2018).

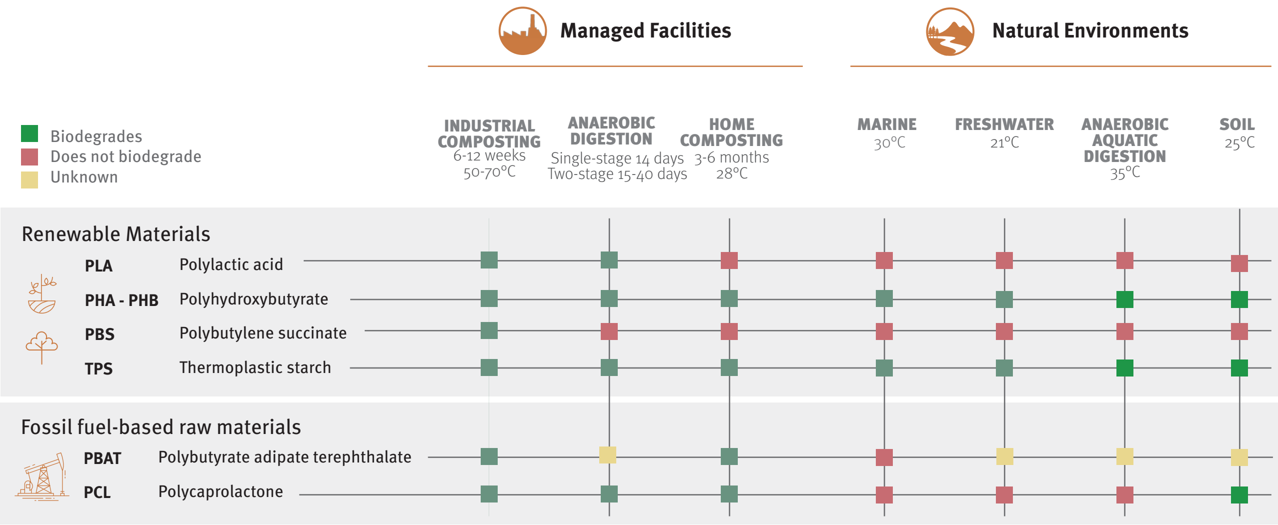
Overall, **the relative environmental performance of bio-based and fossil fuel-based plastics is not well established** as studies considering the entire life cycle (i.e. including end-of-life) are limited. A review of 17 published packaging LCA studies comparing bio-based plastics (both biodegradable and non-biodegradable) to fossil fuel-based plastics was not able to conclusively determine whether bio-based or fossil fuel-based plastics are environmentally preferable (Vendries *et al*. 2018). Similarly, in their review study Walker and Rothman (2020) found variations between polymer types and between fossil-based and bio-based polymers to be so extensive that it was not possible to conclusively declare any polymer type as having the least environmental impact across any of the seven impact categories analysed in the review. Both review studies identify methodological differences in the LCA studies as a key source of variation and uncertainty (Vendries *et al*. 2018; Walker and Rothman 2020). It should also be noted, that **current bio-based plastic production and processing technologies are less established than traditional fossil fuel-derived plastic technologies, and efficiencies and overall environmental impacts continue to improve** (Hermann, Blok, and Patel 2010).

A major part of the rationale for bio-based plastics is their ability to biodegrade, i.e. to safely breakdown and not remain in the environment for hundreds of years, as with fossil-based plastics. However, many biodegradable bio-based plastics only degrade effectively under specific conditions and/or when processed using specific technologies (see Figure 7). Nonetheless, **biodegradable bio-based plastics have potential to be composted at end-of-life, which is particularly beneficial if the packaging is contaminated with food waste,** as this allows the food waste and packaging waste to be **co-disposed**. However, even here, LCA studies are inconclusive in their findings. When the disposal of biodegradable packaging is considered alongside food waste, then composting and other novel co-disposal waste management options show clear benefits (e.g. the use of PLA as insect feed to offset corn consumption) (Bishop, Styles, and Lens 2021). However, when the biodegradable packaging is considered alone, as with non-biodegradable bio-based plastics, studies show divergent impact results and indicate reduced impacts in certain categories and increased impacts in others (Hottle, Bilec, and Landis 2017; Vendries *et al*. 2018).

Nonetheless, studies looking specifically at comparing end-of-life options indicate the importance of disposal impacts, especially for plastics that are biodegradable. Notably, "improved" end-of-life management practices, such as composting, may not result in the lowest environmental impacts (Hermann, Blok, and Patel 2010; Hottle, Bilec, and Landis 2017; Vendries *et al*. 2018). The review of Vendries *et al*. (2018) that looked at 10 studies comparing potential end-of-life options of compostable and non-compostable materials found that composting did not consistently result in significantly lower impacts for bio-based and biodegradable plastic packaging. However, composting was found to be preferable to landfill or incineration, since bio-based and biodegradable packaging that is landfilled or incinerated generally had higher impacts than non-compostable packaging that is landfilled, recycled, or incinerated (Vendries *et al*. 2018). Furthermore, **biodegradable bio-based plastics may disrupt recycling systems set up for fossil fuel-based plastics,** especially notable since recycled plastic packaging options are shown to be environmentally preferred to compostable plastic packaging options in a number of studies (Hottle, Bilec, and Landis 2017; Vendries *et al*. 2018).

Figure 7: Bio-based plastics and their biodegradation.

Source: UNEP (2021a)



🟩 Biodegrades
🟥 Does not biodegrade
🟨 Unknown

		Managed Facilities: INDUSTRIAL COMPOSTING 6-12 weeks 50-70°C	Managed Facilities: ANAEROBIC DIGESTION Single-stage 14 days Two-stage 15-40 days	Managed Facilities: HOME COMPOSTING 3-6 months 28°C	Natural Environments: MARINE 30°C	Natural Environments: FRESHWATER 21°C	Natural Environments: ANAEROBIC AQUATIC DIGESTION 35°C	Natural Environments: SOIL 25°C
Renewable Materials								
PLA	Polylactic acid	🟩	🟩	🟥	🟥	🟥	🟥	🟥
PHA - PHB	Polyhydroxybutyrate	🟩	🟩	🟩	🟩	🟩	🟩	🟩
PBS	Polybutylene succinate	🟩	🟥	🟥	🟥	🟥	🟥	🟥
TPS	Thermoplastic starch	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Fossil fuel-based raw materials								
PBAT	Polybutyrate adipate terephthalate	🟩	🟨	🟩	🟥	🟨	🟨	🟨
PCL	Polycaprolactone	🟩	🟩	🟩	🟥	🟥	🟥	🟩

As with LCAs on conventional plastics, the available LCA studies on bio-based plastics focus on ideal or scenario-led waste management (e.g. 100% composted or 100% landfilled). The environmental impacts of littered or mismanaged bio-based plastics are not captured in the results. This is significant as **most bio-based and biodegradable plastics do not degrade substantially faster than fossil-based plastics** when they land up in the natural environment (see Figure 7). That is, unless the conditions for biodegradation are met (e.g. as in an industrial composter), biodegradable plastics fragment into microplastics and present the same risks as conventional plastics. This is particularly of concern as some evidence suggests that marking a packaging as biodegradable has the potential to increase littering by 20% (NORSUS 2021). Although PLA is found to have lower potential marine plastic litter impacts than PP (in terms of its physical effects on biota) (see Section 3.4.1), evidence from other studies suggests that degradation in oceans and soils is still not sufficiently fast enough for most biodegradable plastics not to present the same risks as conventional plastics to biodiversity and ecosystem functioning (UNEP 2021a). Furthermore, **bio-based and biodegradable plastics seem to present the same – or even higher – chemical threat as conventional plastics** (Zimmermann *et al*. 2020). Health and biodiversity impacts arising from additives to plastics are currently not well captured (if at all) in LCAs (partly due to a lack of information on the type and amounts of chemicals added to polymers, and partly due to gaps in impact assessment methods). This is true for both conventional (fossil-based) and bio-based plastics.

Recommendations on bio-based and biodegradable food packaging

The potential for bio-based and biodegradable food packaging to minimize the environmental impacts of the food system as a whole (through the co-disposal of food waste and packaging waste) represents an opportunity that should be explored. In particular:

- The potential increased use of bio-based and biodegradable packaging should be explored for food packaging types for which recycling is low/difficult, such as contaminated packaging (meat, dairy etc.) and small-format packaging (sweet wrappers).

- It is **imperative that the infrastructure needed for the co-disposal of food and biodegradable plastic packaging is developed before/alongside any promotion of or support for bio-based and biodegradable food packaging**. This includes both industrial composting infrastructure, as well as household collection systems, and most importantly, consumer buy-in and education so that consumers separate out their biodegradable packaging and food waste, from their general waste and dry recyclables.

- Related to the above, it is **essential that any promotion/support of bio-based and biodegradable packaging comes with regulations around labelling and education of consumers**, so that biodegradable plastics do not disrupt conventional plastic recycling systems or end up littered or in landfills. This is imperative since, **from an LCA perspective, bio-based and biodegradable packaging that ends up littered or in the general waste stream will have the same or even higher impacts than conventional plastics** (the latter especially true if they end up in a landfill). Because of the high likelihood of confusion and of consumers not reading labels, it is imperative that regulations are geared towards making it clear and simple for consumers to comply. For example, there is likely to be confusion if some films for meat are compostable and others are not, or if films for meat are compostable but not films for ready meals.
- Wider aspects not necessarily covered by LCA studies, such as social and gender aspects, should be researched and fully understood before the promotion of any new materials on the market, including the potential health impacts of chemicals leaching from biodegradable plastics on various consumer groups based on their sex and age.

3.3 REUSABLE AND RETURNABLE PACKAGING IN FOOD SYSTEMS

Reusable packaging has declined over recent decades, replaced by cheap and convenient single-use packaging (Coelho *et al*. 2020). Single-use packaging dominates supermarket food packaging almost completely, with reusable packaging only evident in small niche applications (see Table 14 for examples). This reliance on single-use packaging for food is increasingly being challenged, as the environmental impacts resulting from single-use plastics are becoming more and more evident, demanding a **change to innovative reusable food packaging systems.**

Currently **there are relatively few LCA studies comparing reusable supermarket food packaging systems to single-use packaging systems** (see Table 14). Nonetheless, an environmental preference for reusable packaging systems over single-use packaging systems has been concluded by a number of studies looking at a wider array of packaging systems (Zero Waste Europe 2020; Upstream 2021). Many studies also identify potential economic benefits and market opportunities for reusable packaging systems (Ellen Macarthur Foundation 2019; Coelho *et al*. 2020). Reusable food packaging systems do however come with increased complications, most notably around **food safety. For this reason, most of the reusable packaging solutions that have made it onto the market have focused on non-food products**, e.g. detergents and personal care products (Coelho *et al*. 2020). Nonetheless, an increasing number of companies pioneering reusable packaging systems are proving that such systems are technically and economically feasible for a range of food products (See Box 2 and Box 3).

Coelho *et al*. (2020) classifies **four types of reusable packaging** (Table 14). A useful distinction in reusable packaging typologies is between “Reused by Consumer” and “Taken back by Business” (Zero Waste Europe 2020). The first two types of reusable packaging in Table 14 (refillable by bulk dispenser and refillable parent packaging) fall under “Reused by Consumer”, where it is up to the consumer to choose the product with less packaging and refill their container. The second two types of packaging in Table 14 are distinguished by their need for a take-back business model that allows the packaging to be collected, cleaned, maintained and returned to the product line. The reusable packaging under the “Taken back by Business’’ category thus needs to be part of a company’s business model to make the system work as they require return logistics and infrastructure for cleaning, maintaining and storing the packaging (Zero Waste Europe 2020). “Taken back by business” reuse systems are thus more costly to implement than “Reused by Consumer” reuse systems.

Box 2: Algramõ

Algramõ (https://algramo.com) is a Chilean company offering a dispensing system as a cost-effective and convenient refill alternative to single-use packaging. The idea behind the brand – in addition to avoiding plastic waste – is for areas of low-income families to have access to basic necessity products, making it possible to buy only the quantity needed, without paying for the packaging. Algramõ works through smart packaging, equipped with "packaging as a wallet technology". "Packaging as a wallet" works through the reusable plastic container being embedded with a Radio Frequency Identification (RFID) chip that, when used together with Algramõ's smartphone app, also becomes a digital wallet. At the Algramõ dispensers, customers choose which product they want and how much they want to refill, and can pay using the smart packaging and app or at the till. Algramõ have partnered with big brands such as Unilever, Nestlé and Walmart. At the moment products such as laundry detergents are available in Chile (both in-store and for home delivery) and at a single Lidl store in the UK (with more locations planned).

https://algramo.com/

Box 3: LOOP

Loop (exploreloop.com), a TerraCycle company, aims to change the way people shop by offering favourite brands in reusable and durable packaging. Loop has partnered with well-known brands, such as P&G, Nestlé, PepsiCo, Unilever, and retailers such as Kroger and Walgreens (USA), Tesco (UK), Carrefour (France), to offer purchases in refillable packaging in a growing number of countries (United Kingdom, France, Canada, the United States, and Japan). Other partnerships include fast food restaurants, such as MacDonald's and Burger King, and operation partners, such as DHL or Ecolab amongst others.

The goal behind Loop is to make reuse easy, convenient and affordable, i.e., to make reuse feel like disposability with the ability to "buy anywhere and return anywhere". A central idea behind the offering is to move packaging from being perceived as a Cost of Goods Sold to being perceived as an asset, thereby enabling reusability, stylish design and innovation. Thus, Loop products aim to offer an elevated customer experience along with reuse. Loop works with brands in an onboarding process to move from single-use to reusable packaging, and distribute their new product via Loop retailer partners and/or direct to consumer (DTC). Consumers purchase products at any Loop integrated channel, e.g., in a physical store of a retail partner or brand. The consumer then returns the empty packaging to the nearest Loop Return Point, e.g., at the partner retail store, and gets their deposit refunded using the Loop Deposit App.

The Loop operational model removes the hassle for the brands by taking care of reverse logistics, sorting, storing and cleaning empty packaging at the Loop distribution centre, and shipping clean packaging to the brands to be refilled. The Loop fee for brands is determined by the durability and washability of the packaging. Packaging that is difficult to clean will likely incur a higher cost per cycle than easy-to-wash packaging.

Image: Grocery aisle promoting products for a circular economy. Supplied by LOOP

Table 14: A classification of reusable packaging (Coelho *et al*. (2020) and Zero Waste Europe (2020))

	Reused by consumer		**Taken back by business**	
Type of packaging	**Refillable by bulk dispenser** (loose distribution)	**Refillable parent packaging**	**Returnable packaging**	**Transit packaging (transport packaging)**
Packaging description	Customers bring their own container or purchase a bag, thereby minimizing or eliminating the packaging customers have to take home. Packaging is still required to transport product to point-of-sale and to fill the bulk dispensers.	The refill packaging is made with less material than the parent packaging. Customers refill the parent packaging at home, e.g. by pouring product inside parent packaging.	Customers return empty packaging (such as containers and bottles) to be cleaned and refilled for future use by the retailer/producer (can be combined with a deposit system to provide a financial incentive).	Customers receive the product in reusable packaging (e.g. boxes, containers, soft packages) which are returned by door-to-door delivery/pick up, or through the post office. Customer reuses packaging (such as crates, pallets and wrappers) multiple times before these are returned to the producer or disposed of.
Product and company examples	Cereals, grains, dry pasta, candy, wine, juice, mineral water, olive oil, vinegar, detergent, hair care products, body and face lotion Algramō: https://algramo.com OU: https://original-unverpackt.de/ MIWA: https://www.miwa.eu/	Makeup, dental floss, tooth and mouth wash tabs, deodorant, perfume, cosmetics, cleaning products, hair care products, flavoured water Blueland; https://www.blueland.com/ Replenish: http://replenishbottling.com/	Beer, soft drinks, mineral water, perishables, detergent, soap, cosmetics, hair care products Loop: https://loopstore.com/ the wally shop: https://thewallyshop.co/	Reusable packaging for transport or shipping of perishables or non-perishables. This can be business-to-consumer (B2C), e.g. e-commerce delivery, or business-to-business (B2B) transport from producer to warehouse to store. Liviri: https://liviri.com/ Euro Pool Group: https://www.europoolgroup.com/ Svenska Retursystem: https://www.retursystem.se/en/
Studies covering reusable alternatives included in the meta-analysis	Dolci *et al.* (2016) Scharpenberg *et al.* (2021) (summarized in Table 10)	None – application mainly in non-food products	Postacchini *et al.* (2018) Scharpenberg *et al.* (2021) Stefanini *et al.* (2021) (summarized in Table 9)	Abejón *et al.* (2020) Albrecht *et al.* (2013) Del Borghi *et al.* (2021) Koskela *et al.* (2014) Levi *et al.* (2011) Tua *et al.* (2019) (summarized in Table 8)

Refillable by bulk dispenser systems

Refillable by bulk dispenser systems, whereby consumers are able to dispense the amount of product they wish to purchase from gravity bin dispensers at the retail store, offer a potential solution to decrease packaging waste.

The degree to which bulk dispenser systems are beneficial is strongly dependent on the type of food product being dispensed, the type of single-use packaging being replaced and the type of packaging used to fill the dispensers. The packaging of the refill system (bulk packaging plus packaging used by the consumer at the dispenser) must use less material/generate lower impacts than the equivalent single-use packaging system. This has been shown to not always be the case where the single-use packaging being replaced is a plastic bag, but significantly lower impacts are possible where the packaging being replaced is a cartonboard box (Dolci *et al*. 2016). In general, if dispensers are filled with much larger packages made of lower-impact materials than the single-use packaging and the food product is such that the dispensers do not require extensive cleaning, then bulk dispenser systems allow for a significant reduction in both the amount of waste and environmental impacts. Furthermore, if reusable packaging is used to transport product to store and refill the dispensers and/or if customers bring their own reusable containers rather than purchasing a plastic bag, then even more substantial reductions in environmental impacts are possible (provided that washing and returning the reusable packaging to be refilled does not exceed the impact of manufacturing and disposing the single-use packaging).

Refillable by bulk dispenser systems also have potential customer benefits, in that a customer can purchase only the quantity of the product they require. Although not quantified by any of the LCA studies considered in the meta-analysis, this may lead to lower food waste, and consequently further reduce the environmental impacts of the bulk dispenser system. However, self-dispensing systems are arguably less convenient to consumers, especially if these result in additional queues for customers (e.g. to weigh bags at the dispenser) and also raise hygiene concerns if not well managed (e.g. insect infestations in rice).

The contexts under which refill by bulk dispenser is preferred to single-use food packaging are summarized in Table 15.

Table 15: Preference for refill by bulk dispenser (loose distribution) depending on context

This matrix, based on LCA findings, helps to identify the closest scenario and option with the lowest environmental impacts given a certain context. The content of the matrix is simplified. Please refer to the full narrative of the UNEP meta-analysis for details.

🟦 **Minimising food waste is a priority issue to** 🟩 **be addressed through packaging**
Packaged products preferred

	Food product suitable for a dispensing system (e.g. pasta, cereals, pulses etc.)			**Not suitable**
Waste Management Context	**LOCAL MARKET**	**INTERNATIONAL MARKET** OR **NATIONAL MARKET IN LARGE COUNTRY**	**CUSTOMER UNWILLING TO USE REUSABLE CONTAINER** AND/OR **INEFFICIENT BULK TRANSPORT PACKAGING**	**FOOD PRODUCT NOT SUITED FOR DISPENSING** (e.g. sticky product requiring intensive cleaning of dispenser)
POOR WASTE MANAGEMENT (landfill and open dumping; poor/no recycling or recovery)	Product dispensed into reusable container; product transported in bulk **reusable plastic containers**	Product dispensed into reusable container; Product transported in bulk **cardboard boxes**	As simple packaging as possible without increasing food loss, e.g. **plastic bag**	
GOOD WASTE MANAGEMENT (high recovery rates and strong recycling markets)	Product dispensed into reusable container; Product transported in bulk **reusable plastic containers or cardboard boxes** (with high recycled content)	Product dispensed into reusable container; Product transported in bulk **cardboard boxes** with high recycled content	As simple packaging as possible without increasing food loss, and with high recycled content (especially if fibre-based), e.g. **plastic bag or carton**	

Returnable packaging

Whether or not returnable packaging shows environmental benefits depends on the type of packaging and on the logistics (especially the transport distances, modes of transport and reverse logistics). Whilst only two LCA studies on returnable food packaging are covered in this meta-analysis, returnable food packaging has many similarities with returnable beverage packaging. In a wider study – looking at all types of returnable packaging – the **number of times the packaging is refilled, the return transport distances** (between collection, cleaning, refilling and point-of-sale), and **the energy and water efficiency of washing** were all found to be important parameters (Zero Waste Europe 2020).

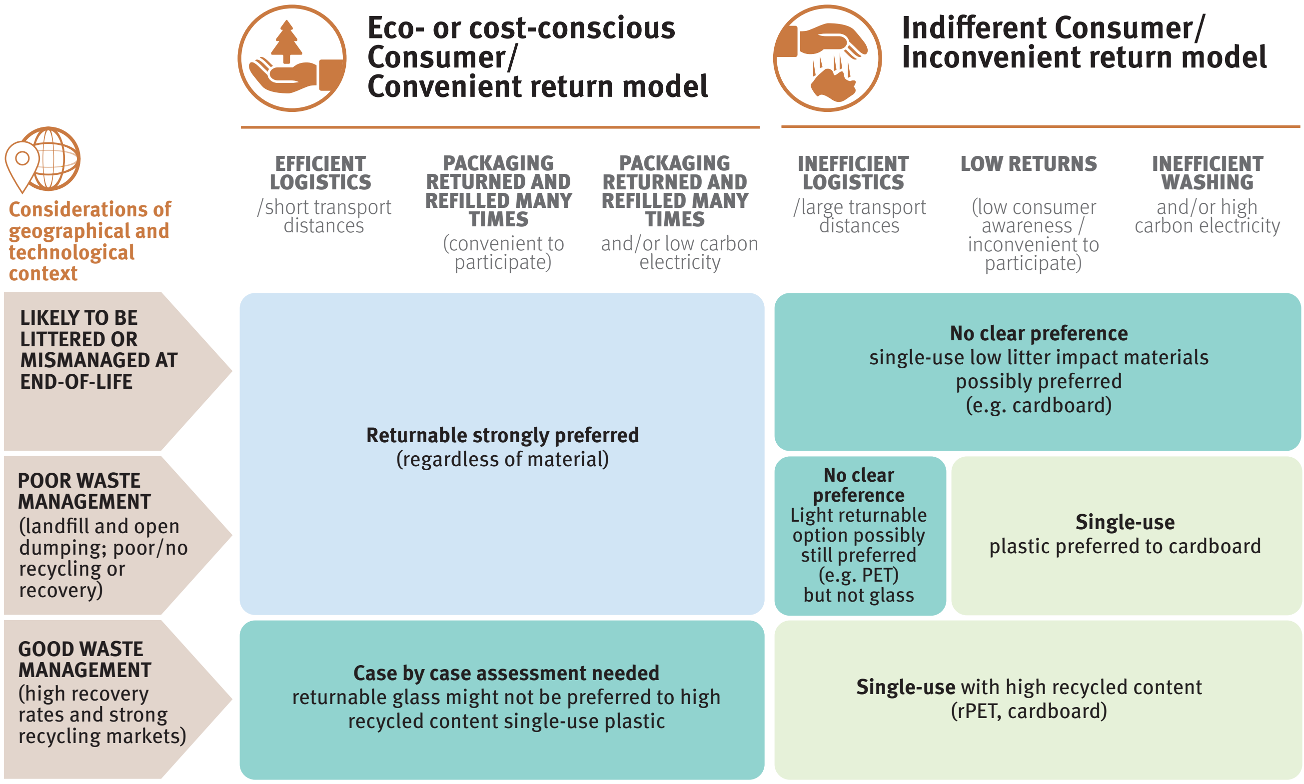
Where transport distances between use, collection and logistics centres are minimal, and reuse factors are high, the environmental benefits of returnable packaging over single-use packaging can be considerable. For a representative package in their integrated in-store retail model, Loop found a greater than 45% reduction in climate change impact, relative to a traditional single-use in-store retail model. In as few as three uses, Loop refillable packaging can have lower environmental impacts compared to single-use packaging[14].

The contexts under which returnable food packaging is preferred to single-use food packaging are summarized in Table 16.

Table 16: Preference for single-use or returnable food packaging depending on the context

This matrix, based on LCA findings, helps to identify the closest scenario and most environmentally sound options given a certain context. The content of the matrix is simplified. Please refer to the full narrative of the UNEP meta-analysis for details.

🟦 **Returnable packaging preferred** 🟩 **Single-use packaging preferred** ▨ **No clear preference**



	Eco- or cost-conscious Consumer/ Convenient return model			**Indifferent Consumer/ Inconvenient return model**		
Considerations of geographical and technological context	**EFFICIENT LOGISTICS** /short transport distances	**PACKAGING RETURNED AND REFILLED MANY TIMES** (convenient to participate)	**PACKAGING RETURNED AND REFILLED MANY TIMES** and/or low carbon electricity	**INEFFICIENT LOGISTICS** /large transport distances	**LOW RETURNS** (low consumer awareness / inconvenient to participate)	**INEFFICIENT WASHING** and/or high carbon electricity
LIKELY TO BE LITTERED OR MISMANAGED AT END-OF-LIFE	**Returnable strongly preferred** (regardless of material)			**No clear preference** single-use low litter impact materials possibly preferred (e.g. cardboard)		
POOR WASTE MANAGEMENT (landfill and open dumping; poor/no recycling or recovery)				**No clear preference** Light returnable option possibly still preferred (e.g. PET) but not glass	**Single-use** plastic preferred to cardboard	
GOOD WASTE MANAGEMENT (high recovery rates and strong recycling markets)	**Case by case assessment needed** returnable glass might not be preferred to high recycled content single-use plastic			**Single-use** with high recycled content (rPET, cardboard)		

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[14] Peer-reviewed LCA on shampoo bottle. Personal communication, Ali Golden (Director, Strategic Relationships at TerraCycle)

Reusable transit packaging

Reusable transit packaging has been studied fairly extensively with LCA, albeit mainly in Europe and most often with respect to the transport of fresh fruit and vegetables. **Important aspects to consider are transport distances and logistics** (especially optimizing the return of the reusable crates to minimize transport emissions) as well as **the cardboard recycling infrastructure and recycled content of the cardboard box**. Reusable plastic crates are shown to be environmentally preferred to cardboard boxes for the distribution of fresh fruit and vegetables in local markets (Levi *et al*. 2011; Albrecht *et al*. 2013; Abejón *et al*. 2020; Del Borghi *et al*. 2021)l. 2020; Del Borghi *et al*. 2021). However, the reverse is found (corrugated cardboard boxes preferred to reusable plastic crates) where transport distances are high and the cardboard received credits for recycling at end-of-life (Levi *et al*. 2011; Koskela *et al*. 2014).

Product loss is acknowledged to be an important consideration by many authors but not explicitly addressed in any of the studies. There is however a suggestion that the rounded inner edges and smooth easy-to-clean surfaces of plastic crates, along with their strength and ability to be stacked securely are advantageous in preventing product losses (Albrecht *et al*. 2013; Tua *et al*. 2019).

The contexts under which returnable transit packaging is preferred to single-use food packaging are summarized in Table 17.

Table 17: Preferred type of food transit packaging depending on context

This matrix, based on LCA findings, helps to identify the closest scenario and most environmentally sound options given a certain context. The content of the matrix is simplified. Please refer to the full narrative of the UNEP meta-analysis for details.

🟦 **Returnable transit packaging preferred** 🟩 **Single-use transit packaging preferred** ■ **No clear preference**

Market System Considerations

Waste Management Context	**LOCAL MARKET**	**HEAVY PRODUCT, WITH HIGH REQUIREMENTS FOR PACKAGING QUALITY/STRENGTH**	**INTERNATIONAL MARKET OR NATIONAL MARKET IN LARGE COUNTRY**	**LIGHTWEIGHT PRODUCT WITH LOWER REQUIREMENTS FOR PACKAGING QUALITY,** e.g. allowing a high degree of recycled content
POOR WASTE MANAGEMENT (landfill and open dumping; poor/no recycling or recovery)	**Reusable plastic crates** strongly preferred		No clear preference between **collapsible, reusable plastic crates** and **single-use cardboard boxes**	No clear preference between **single-use wooden crates or reusable plastic crates**
GOOD WASTE MANAGEMENT (high recovery rates and strong recycling markets)			**Single-use** cardboard boxes preferred	

Recommendations on reusable and returnable food packaging

Selling fruit and vegetables loose and, bulk dispensing dry goods should be encouraged, as it is almost always preferred to heavily packaged products, such as tray-and-wrap or bag-in-box single-use packaging. **Returnable primary and secondary packaging should also be supported** as, when implemented in the right context, has significantly lower environmental impacts than single-use packaging systems.

It is essential that the **whole packaging system be considered when making decisions on reusable packaging**; "packaging-free" consumer-facing solutions are not necessarily the best solution unless the transport of product to the point-of-sale is also optimized. Returnable packaging and reusable transport packaging can be a poor option when reverse logistics are inefficient and transport distances in the collection, washing and redistribution are high.

Recommendations to decrease emissions of reusable/returnable packaging and ensure better performance over single-use packaging systems:

- Widespread distribution of washing/distribution plants should be encouraged, as this minimizes the average transport distance from user to inspection/cleaning and back to producer, thereby minimizing transport emissions. More efficient modes of transport (e.g. rail or barge over road), lower-carbon fuels (e.g. biofuels) and electric vehicles can further improve the environmental performance of returnable/reusable packaging systems.

- The **use of renewable energy in washing/reconditioning plant should be promoted**, as this will decrease the impacts of reusable crates, e.g. solar panels, and Combined Heat and Power (CHP) plants in the treatment of wastewater sludge and crate residues.

Recommendations to create a level playing field for reusable packaging systems:

In general, **a level playing field must be created for reusable packaging systems**, both in terms of their cost and convenience relative to single-use packaging systems, and in terms of legislative environment, which tends to favour single-use packaging systems.

- **Standardization of packaging is recommended**, as his has been shown to increase reuse rates and decrease costs of reusable packaging systems. Furthermore, standardization allows **pooling** (where different companies share the same resource in order to optimize operations and costs) and deposit return schemes (in which a company/customer "rents" rather than owns the packaging). Both have been shown to be highly effective in driving up return rates and reducing emissions (through better logistics). Although it is recognised that standardization can be challenging as it hinders branding and product recognition. So innovation on how to keep branding and product recognition high, while using a more standardized packaging should be encouraged. Since standardization requires co-operation between brands it requires strong policy support and a conducive legislative environment.

- **Reusable food packaging systems should be competitively priced with single-use ones.** Reward systems, such as offering discounts for future purchases or for purchases at partner establishments, are an option for brands/retailers. Deposit return schemes, in which a customer receives their money back when the packaging is returned, have also been shown to be successful. Creating equitable pricing can also be done through legislation that creates the right economic incentives, e.g. tax breaks on products sold in reusable packaging**.**

- **Reusable food packaging systems must be accessible and convenient** to consumers to take the reusable option and especially to return the packaging, else they are likely to fail. The use of **smartphone apps** and other technology, such as internet of things (IoT), including **smart tags** for tracking and tracing packaging rotations and for verifying reuse rates, are already being used to great success. Although requiring consumers to download apps for every return scheme they participate in could potentially become a barrier, and IoT solutions add to the cost of reusable packaging. Return schemes at the retailer level or in which several brands participate, such as Loop (see Box 2), are possible ways to overcome these barriers. ECommerce also offers a good opportunity for convenient reusable packaging systems.

Further recommendations for policy makers to address the competitive advantage single-use packaging systems currently benefit from are:

- Put in place economic measures that help remove market barriers for reusable packaging systems, such as **taxes on packaging waste.**

- Create and enforce **standards for food packaging** that address overpackaging and ensure better packaging design.

- Put in place legislation, such as **Extended Producer Responsibility (EPR)**, that makes companies responsible for the end-of-life of the products they put on the market. Such legislation typically includes targets for recovery, recyclability and/or recycled content. **EPR legislation needs to include concrete measures to stimulate reuse, e.g. quantitative reuse targets, as this is lacking in most countries that have implemented EPR, as well as requiring reusable packaging to also be recyclable at end-of-life.**

3.4 MARINE LITTER IMPACTS

Although the LCA method has evolved in the past decades, it does not yet include a methodology to assess the consequences of plastic waste leaked into the environment (i.e. litter) on ecosystems and human health.[15] This limits the application of LCA as a complete tool to compare the potential impacts of single-use plastics and their alternatives. Therefore, in recent years different organizations across the globe have made efforts to address the shortcomings of LCA regarding plastic litter (NORSUS 2021). On the inventory side, in 2020 the **Plastic Leak Project** proposed guidelines to quantify different types of macro- and microplastic litter emissions (Plastic Leak Project 2020).

This section of the meta-analysis focuses on investigating how LCA results would change if we were to include marine litter impacts among the impact assessment categories considered in some of the existing LCA studies on supermarket food packaging. To achieve that, UNEP partnered with the international working group MarILCA (MARine Impacts in LCA)[16]. MarILCA was formed in 2018, supported by the UNEP Life Cycle Initiative and the Forum for Sustainability through Life Cycle Innovation (FSLCI), with the goal to integrate potential impacts of marine plastic litter into LCA (Boulay *et al*. 2019; Boulay, Verones and Vázquez-Rowe 2021).

An initial approach to addressing potential marine plastic litter impacts has been by means of a "litter indicator", e.g. employed in LCA studies comparing plastic straws, bags and bottles to non-plastic alternatives (Civancik-Uslu *et al*. 2019; Chitaka, Russo, and von Blottnitz 2020; Zanghelini *et al*. 2020; Stefanini *et al*. 2021). **The litter indicators** vary in their complexity but generally **consider the propensity for littering (leakage rate) and the degradability of the material.** A typical outcome of studies including a litter indicator is that the plastic alternative(s) rank(s) best on climate change potential but worst on marine litter potential. Thus, litter indicators are a useful way to make the potential "hidden" marine litter impacts of plastic alternatives explicit in the study results, but a decision on the "best" alternative depends on the weight placed on climate (and other) impacts relative to marine litter potential. For example, in their study on bottles made of PET, rPET, non-returnable glass and returnable glass, Stefanini *et al*.(2021) found that rPET bottles have the best performance in all impact categories considered (global warming, stratospheric ozone depletion, terrestrial acidification, fossil resource scarcity, water consumption and human carcinogenic toxicity), followed by PET bottles and returnable glass bottles. However, the returnable glass bottles have the best performance with respect to the marine litter indicator.

The MarILCA framework proposes to add to the relevant existing LCA categories (e.g. human toxicity, ecotoxicity) new impact categories (e.g. physical effects on biota) (Woods *et al*. 2021). Among these impact categories, physical effects on biota has shown particular progress[17], and is used in this meta-analysis to include physical impacts of microplastic marine litter in existing case LCA studies which had not included marine litter impacts yet. The new impact category ***physical effects on biota*** aims at capturing the **physical impacts of plastic litter on marine organisms, both through internal (ingestion) and external (entanglement, smothering) pathways** (Woods *et al*. 2021).

3.4.1 Insights from case studies integrating marine litter impacts into existing LCA categories

Since LCIA methodologies for the assessment of potential impacts of marine plastic litter are still under development, studies on marine litter impacts of food packaging are scarce. Recently, an LCA study of single-use food trays (coordinated by MarILCA) included the potential impacts of microplastic emissions for the first time (Corella-Puertas *et al*. 2022). Through the partnership between UNEP and MarILCA, a similar methodology is applied to two of the food packaging LCA studies considered in the meta-analysis: Abejón *et al*. (2020) and Vigil *et al*. (2020). The two LCAs are used as a base, with the *physical effects on biota* impacts of microplastic emissions added to the results to assess the potential marine impacts of single-use food packaging and their alternatives (Corella-Puertas and Boulay 2022). A snapshot of the results of the study by Corella-Puertas *et al*. (2022), and of the two case studies developed as part of the meta-analysis are provided in Appendix C. Full results can be found in Corella-Puertas *et al*. (2022) and Corella-Puertas and Boulay (no date).

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[15] LCIA methods typically include a range of impact categories that capture potential adverse human health effects, such as carcinogenicity, toxicity and respiratory illnesses. These are not differentiated according to gender and age in LCIA methods, although it is recognised that certain health impacts – notably chemicals from plastics – affect different segments of the population differently, with women, small children and those undergoing puberty, especially susceptible to negative health outcomes (UNEP 2016).

[16] The results of this partnership will be presented at LCA Foods 2022 in Lima, Peru in October 2022 (Corella-Puertas *et al*. 2022).

[17] Progress of the new impact category '*physical effect on biota*' is shown in recent publications on preliminary microplastic fate (Corella-Puertas *et al*. 2022), micro- and nanoplastic exposure and effects (Lavoie, Boulay and Bulle 2021) and macroplastic exposure and effects (Høiberg, Woods and Verones 2022)

It is important to highlight that the LCA case studies informing the insights and recommendations presented below evaluate only one type of the potential impacts of marine plastic litter – physical effects on biota impacts of microplastic emissions on aquatic species. MarILCA is currently developing methodologies to assess other potential impacts of plastic litter, such as (Woods *et al.* 2021):

- Physical effects on biota impacts of macroplastic emissions (linked with entanglement, smothering and ingestion of larger plastics);
- Ecotoxicity impacts of plastic additives and other chemicals adsorbed to the surface of plastics;
- Invasive species impacts (linked with organisms that are attached to the surface of plastics and may be carried to locations where they are not native species); and
- Human toxicity impacts of micro- and nanoplastics.

Furthermore, so far, physical effects on biota only cover effects on species present in the water column and at the surface. Future research should cover the effects of microplastic litter on species present in ocean sediments.

The key insights from the three LCA case studies with respect to potential marine plastic litter impacts of single-use plastic food packaging are the following:

- For various polymers, **climate change impacts have the largest overall contribution to the damage on ecosystem quality, whereas marine microplastic litter impacts (physical effects on biota) are several orders of magnitude smaller.** The only exception found so far is EPS, when its physical effects on biota impacts are calculated with worst-case characterization factors[18].
- The **fate and impacts of marine microplastic litter vary depending on the type of plastic.** In the presented case studies, the characterization factors and potential impacts of physical effects on biota provide a preliminary ranking of the different types of plastics, with EPS having the highest potential impacts and PLA the lowest, and PP and HDPE falling between them. PP was found to have slightly lower potential impacts than HDPE, although this finding may not be significant given their high uncertainty. More research is needed to reduce their uncertainty (Corella-Puertas and Boulay no date; Corella-Puertas *et al.* 2022)
- In different regions of the world, littering and waste management practices (formal and informal) differ. The case studies showed that **the location of plastic use and end-of-life can change marine microplastic litter impacts by up to two orders of magnitude.**
- **Indications are that reusable plastics have low marine microplastic litter impacts** (physical effects on biota). This is a result of the lower littering rate and most likely heavier weight of reusable options. Although none of the presented case studies compared single-use and reusable plastics, overall single-use plastics slightly affected the endpoint results, whereas reusable plastic impacts were very small. Based on Abejón *et al.* (2020), even in the worst-case scenario, marine microplastic litter impacts were 3 - 4 orders of magnitude smaller than climate change impacts.

Recommendations on addressing marine plastic litter impacts of food packaging

- Early findings of integrating marine plastic litter impacts into life cycle impact assessment results suggest that **climate change impacts** are still likely to be the **most important** consideration for most materials. **Packaging alternatives that seek to address marine plastic impacts should simultaneously address climate change impacts** (or at least, not to be at the expense of climate change impacts).

- **Reusable plastic packaging alternatives should be promoted over single-use plastic alternatives** as these are likely to have lower marine plastic impacts (resulting from both the quantity and type of plastics from which they are made).

- **The fate and impacts of marine microplastic litter vary depending on the type of plastic**. In the presented case studies, the characterization factors and potential impacts of physical effects on biota ranked the different types of plastics with EPS having the highest potential impacts and PLA the lowest. PP and HDPE fall between these two, with PP found to have slightly lower potential impacts than HDPE in the case studies (although this finding may not be significant). Although uncertainty is still high and all potential marine impacts are still to be incorporated, this information provides a useful counter-balance to strengthen (or weaken) support for different polymers used in food packaging (especially those with a high likelihood of being littered).

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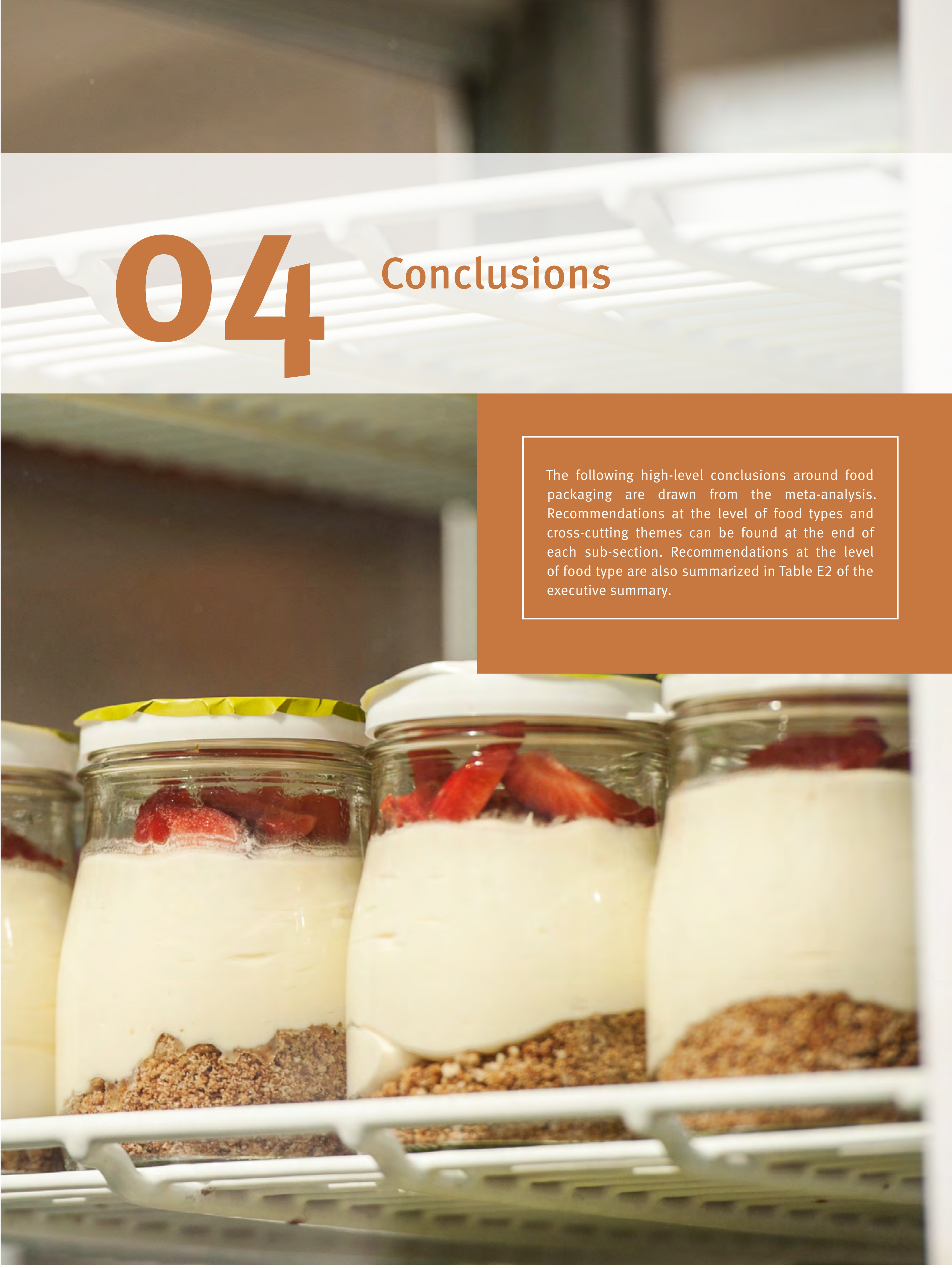
[18] Because of the high uncertainty regarding the fate of microplastics in the environment, characterisation factors are developed at three levels: best case, medium case, and worst case. Please see Corella-Puertas *et al.* (2022) for details on the methodology.



04

Conclusions

The following high-level conclusions around food packaging are drawn from the meta-analysis. Recommendations at the level of food types and cross-cutting themes can be found at the end of each sub-section. Recommendations at the level of food type are also summarized in Table E2 of the executive summary.

For foods such as MEAT associated with high environmental impacts for their production, packaging design should prioritize minimization of food waste. LCAs on meat packaging clearly show that the largest contributor to environmental impact is food waste, with packaging impacts largely negligible. Packaging that extends shelf life and reduces food waste at the retail or household level is preferred even if it is associated with higher environmental burdens. However, it is not sufficient for packaging to just demonstrate ***superior technical properties*** for it to be preferred. ***Consumer behaviour*** and preferences were identified by many studies as a key determining factor in food wastage rates.

For foods such as DAIRY PRODUCTS, with production-related environmental impacts that are comparable to packaging-related environmental impacts, there are no clear LCA recommendations and case-specific investigation is required. When food wastage rates are low, the type of packaging dominates the overall environmental profile, while when food wastage rates are higher, the type of packaging is less important than the minimization of food waste. A general observation from the LCA studies is that single-portion food packaging is preferred over larger packaging if the packaging is of a similar material, uses a similar or smaller amount of packaging per quantity of food delivered and results in reduced food wastage. However, over-packaged single-portion foods have higher burdens even if food waste is minimized. It is also worth noting that small-format packaging tends to have a higher propensity for being littered.

For foods with low environmental burdens in their production, packaging should be minimized. Furthermore, packaging should be eliminated or designed to be reusable wherever feasible, i.e. wherever the impacts of increased food losses and/or logistics operations are not higher than the impacts of packaging avoided. **LCAs on fresh produce packaging** show that significant environmental benefits can be achieved with reusable transport packaging, that can also be used in the retail display of the produce, thereby eliminating the need for consumer-facing packaging. Nonetheless, fresh produce supply chains have been optimized to sell packaged produce and consumers are accustomed to buying it that way. Solutions will need to be found to reconfigure supply chains and store operations, and to make it easy and convenient for people to buy loose produce. It is also essential that consumers are provided best practice guidance on storage (WRAP 2022).

Substituting single-use plastic for other single-use materials does not represent a solution in most cases. LCAs of single-use packaging tend to show plastics having the lowest impacts, mainly as a result of plastics' low weight relative to other materials. Substitutions with cardboard, glass, steel or aluminium tend to show higher impacts, or at best, a trade-off between different impacts. For example, the few recent LCAs that take marine litter impacts into account show that whilst plastic packaging options often have the lowest climate change impact, they have the highest marine litter impacts. This presents a challenge for decision-makers who have to manage trade-offs between impacts in solutions that address competing goals, such as addressing both climate change and plastic pollution. **Innovative packaging solutions** that minimize or avoid single-use packaging altogether rather than changing materials, e.g. returnable packaging, **are required to decrease the life cycle emissions of food products**.

It is **important to increase waste collection and recycling rates to improve packaging sustainability**. Conflicting results for environmental preference between different packaging materials is largely a consequence of different waste management contexts. It is clear, however, that ***higher recycled content in packaging materials leads to lower environmental impacts***. But in many countries recycled content in food packaging is limited by food contact material regulations. This is despite many countries having high recycling targets for food packaging. There is therefore **a need for policy alignment, as well as the development of packaging materials and recycling technologies that enable high recycled content in packaging materials whilst ensuring food safety**.

Achieving high recycled content in packaging requires the availability of high quality recyclate (secondary material). To that end, **packaging needs to be designed for recycling**. Under current designs, it is estimated that 30% of plastic packaging will never be reused or recycled (The World Economic Forum and Ellen MacArthur Foundation 2017). Multilayer and composite materials are particular culprits preventing packaging from being recycled. A further cause is the addition of dyes, pigments and other additives that decrease the quality of the recyclate, thereby decreasing the demand and price for the material, and consequently the likelihood of it being collected for recycling. Improvements in packaging design to address lack of recyclability are switching to single materials; removing dyes, pigments, and other chemical additives; avoiding polymers that are difficult to recycle or lack recycling infrastructure; and using adhesives and making sleeves, labels, caps etc. from materials that are compatible for recycling (e.g. either making them of the same polymer as the main packaging or of materials that are easy to separate in mechanical recycling processes).

For food packaging that is contaminated with food waste and not easily cleaned, bio-based and biodegradable plastics could present a solution for co-disposal of food waste and packaging that results in overall lower climate change impacts. Washing contaminated packaging increases both the costs and environmental impacts of mechanical recycling processes, e.g. increased water use and emissions to water, as well as energy for heating and washing. Co-disposal removes the need to clean the plastic, however, composting requires sufficient waste management infrastructure in place to support the separate collection and treatment of this waste stream. Consumers would also need to be educated and amenable to sorting and separating their food packaging waste. To this end, **it is essential that any promotion/support of biodegradable packaging comes with regulations geared towards making it clear and simple for consumers to comply.** For example, labelling requirements and standardisation across packaging types. For example, there is likely to be confusion if some films for meat are compostable and others are not, or if films for meat are compostable but not films for ready meals.

When changes are made to packaging designs with the intention to reduce their environmental impacts, it is essential that acceptability to consumers and potential indirect effects be taken into consideration. Such indirect effects include the influence of packaging on how consumers transport, store and prepare food, and how they clean, separate and dispose of packaging and food waste. LCAs tend to show that bigger packaging sizes have lower environmental impacts. Partly because of the better material efficiency of larger packaging sizes (less packaging per kg of product), but also because of fewer trips to the supermarket, i.e. where consumer transport is included, buying a large amount means less kms travelled per kg of product. However, where larger pack sizes lead to more food wasted in the home then the environmental gains of better material efficiency/fewer car trips are overturned by the environmental burdens associated with producing extra food (since for most food products, the environmental impacts associated with producing the product are much higher than producing the packaging). It is vital that decision-makers keep this in mind, as counter-intuitively, small pack sizes – or **buying just the right amount of product**, as in loose purchase systems – may lead to the lowest environmental impact overall if they prevent food waste. Similarly, where a packaging design causes higher food waste, e.g. where it is difficult to extract the full contents from the package, any benefits of the packaging materials are likely to be overturned by the environmental impacts of producing the wasted food. Shelf life studies are also important to accurately determine the extent to which alternative packaging extends shelf life at both the retailer and household. These indirect effects are currently not well reflected in LCA studies.

Packaging alternatives that seek to address marine plastic impacts should simultaneously address climate change impacts (or at least, not be at the expense of climate change impacts). The case studies integrating marine plastic litter impacts into life cycle impact assessment results indicate that climate change impacts are still likely to be the more important consideration for most packaging materials.

Although the findings should be taken as preliminary, PLA is indicated to be the preferred plastic material in terms of its physical effects on biota, with the lowest potential impacts, and EPS the least preferred, with the highest potential impacts. PP and HDPE fall between these two, with PP found to have slightly lower potential impacts than HDPE in the case studies (although this finding may not be significant).

Inconsistent findings of LCA studies are most often a result of different modelling choices applied in the studies. The way in which recycling is modelled, especially the application of credits to packaging recycled at end-of-life and to packaging with recycled content, can change the outcome of comparisons between different material types and disposal routes. **Standardisation of methods in the assessment of packaging systems is required**. This is especially important for bio-based and biodegradable plastics, with inconsistent LCAs unable to provide clear assessments on the potential benefits (or otherwise) of novel packaging materials as compared to traditional packaging materials.

When assessing alternative packaging options with LCA, the recommendations must be combined with a series of other context specific considerations. For instance, social impacts and gender analysis are not generally covered by LCA studies, and yet remain highly important aspects in policy-making. A better understanding of gender roles, gender-differentiated health risks, as well as consumer behaviours are essential considerations to further contribute to shifting from single-use plastic products to reuse models. For instance, utilizing a gender lens to design different targeted communication and education strategies can enhance the information, motivation, and skills needed so that consumers can make better decisions around reuse, recycling and waste disposal, thereby unlocking long-term behavioural changes (UNEP 2021b).

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Image: Stacked plastic crates loaded for delivery. (volkansengor, iStockphoto.com)

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Appendices

Appendix table of contents

List of Appendix Figures

List of Appendix Tables

Appendix A: **Overview of LCA**

Life Cycle Assessment (LCA) is a well-established tool for assessing the potential environmental impacts associated with a product or service, providing a structured framework within which to model its consequences on the natural environment and society. All stages of a product's life cycle are considered, from mining, extraction or growing of raw materials to its manufacturing, distribution and use, right up to the final disposal of its components. LCAs have a number of benefits, including the following:

- creating awareness that decisions are not isolated, but that they influence a larger system
- promoting decision-making for the longer term, by considering all environmental issues and potential knock-on effects associated with a decision choice
- improving entire systems, and not just single parts of systems, by avoiding decisions that fix one problem but cause another unexpected issue

An LCA identifies the impacts and significance of each life cycle stage of the product analysed and makes possible comparisons with different products or systems and between different materials. International standards on LCAs (ISO 14040 and ISO 14044) divide LCAs into four main stages:

- **Goal and scope definition:** Objective (goal) and the methodological approach (scope).
- **Inventory analysis:** All raw materials and emissions (inputs and outputs) are considered for each of the unit processes that make up the life cycle of the product. Inputs include the use of natural resources, such as land and water, as well as manufactured materials such as fuels and chemicals. Outputs are released to air, water and land, as well as all products and by-products. Taken together, these unit processes make up the life cycle system to be analysed, as defined by the product system boundary. The life cycle inventory (LCI) is a comprehensive list of resources and emissions (inputs and outputs).
- **Impact assessment:** The LCI is assessed by connecting resources and emissions to their corresponding impacts on the environment and human health. In this way, the inputs and outputs are summed up into common areas of environmental concern such as impacts on human health, impacts on ecosystems, etc. This can be done at varying degrees of complexity, and a number of different life cycle impact assessment (LCIA) methods have been developed to quantify the potential environmental impacts of a product system.
- **Interpretation:** Findings are evaluated in relation to the defined goal and scope in order to reach conclusions and make recommendations.

It is important to note that, although the LCA method is standardized, there is still room for a range of methodological choices that have an impact on the results. Additionally, LCAs predict *potential* environmental impacts or damages, as the necessarily global nature of the predictive LCIA models means they do not take the specific receiving environment into account. Life cycle inventory data (the basis for impact assessment) span multiple geographical locations across countries and continents in today's global supply chains, thus LCIA's predictive models are not like environmental impact assessment (EIA) models that accurately characterize the actual risks associated with emissions at a particular location. Indeed, the value of an LCA study lies not so much with the final numbers, but rather with the exploration and consequent understanding of the system it assesses. **Especially valuable is an LCA's ability to highlight hotspots along the value chain** (i.e. show the areas of highest potential impact), and also to **highlight trade-offs between different impacts.** It is seldom that one system or decision option performs better than another in all aspects of environmental impact. Understanding these trade-offs is a prerequisite towards improving the sustainability of product systems.

Appendix B: **Food packaging LCA studies**

This appendix presents the LCA studies covered in the meta-analysis. For each study a short description is provided together with a summary of the results and main conclusions. A tabular summary is included for each study, which presents further details on the products studied. Results are summarized using colour coding to depict the relative performance of products across the impact indicators considered in the study. Note that the colour coding only denotes relative and not absolute impacts and the reader is referred to the original publication to appreciate the range and scale of the impacts calculated by the studies.

Highest relative impact	🟥
In-between (neither highest nor lowest)	🟨
Lowest relative impact	🟩

B.1 REFRIGERATED PRODUCTS

B.1.1 Meat products

Environmental impact of biodegradable food packaging when considering food waste: Dilkes-Hoffman *et al.* (2018)[19]

The premise of this paper is that bio-based and biodegradable plastic packaging has a role to play in replacing conventional multi-layer plastic packaging that is non-recyclable and non-degradable. This is in recognition of the fact that most plastic food packaging is not suitable for recycling and has limited waste management options available to it. The study focuses specifically on the GHG trade-offs between the following types of packaging for beef and cheese:

- traditional polypropylene (PP) packaging and
- biodegradable packaging made of thermoplastic starch (TSH) and polyhydroxyalkanoate (PHA).

TSH and PHA were selected as together they provide the same functionality as conventional multi-layer plastic packaging: TSH is considered to have the best oxygen barrier properties of all polymeric materials and PHA the best water barrier properties out of all biodegradable polymers. In addition, both these polymers are seen to degrade in sea water, and therefore likely to have lower impacts on marine environments than conventional plastics. The life cycle included the portion of food waste generated, but not the fraction of food consumed. The default end-of-life assumption for both the food and the packaging was landfill with no methane capture. Alternative end-of-life scenarios investigated were landfill with methane capture, composting and anaerobic digestion for the bio-based plastic packaging and food waste. Table B1 summarizes the main parameters and results of the study for beef.

Summary of results and conclusions

This study confirmed that for beef, **the impacts of the food waste far exceeded that of the packaging** for both types of packaging. Direct comparison of the packaging types showed that there is little difference in the packaging production phases between the two types of polymers (conventional and bio-based). However, the impacts associated with bio-based polymer production show a much wider range due to the variability associated with the feedstock and production method. Similarly, the end-of-life assumptions impact significantly on the overall bio-based packaging GHG emissions. When bio-based and biodegradable plastics are sent to landfill they can degrade and release methane. In contrast, fossil-based plastics are largely inert. If landfill gas capture is included, then the emissions associated with the end-of-life of bio-based and biodegradable plastics would be substantially reduced.

The study shows that if food waste in the bio-based and biodegradable packaging is decreased by just 6% then the emissions associated with the biodegradable packaging in landfill can be negated and the overall outcomes are identical for both packaging types. The starch-based polymer packaging is reported to result in a 15% improvement in shelf life. Therefore, it is likely that the decrease in GHG emissions from reduced food waste outweighs the GHG emissions associated with the production and disposal of the PHA-TSH packaging.

The GHG emissions could also be decreased if the food wastage was processed more efficiently through processes such as composting and anaerobic digestion.When looking at the water use for each of the plastics, it could be seen in the study that the **contributions of the production of PHA-TSH packaging to the overall water use was 60% higher than the water use required for the production of PP packaging.**

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[19] The relatively few studies considering bio-based and biodegradable plastics and food waste led to the decision to include this study in the meta-analysis even though it does not fully meet the selection criteria (it considers only greenhouse gas emissions and water use).

APPENDIX B

Table B1: Summary table: Dilkes-Hoffman *et al.* (2018)

		Products considered in study	
		PP Package	PHA-TPS Package
		Beef	Beef
Study scope	Materials	Polypropylene	Thermoplastic starch, PHA
	Functional unit (FU)	1 kg of packaged product at the house	
	Weight [grams]	58	57.7
		-	(PHA 11.5, starch 27.6, glycerol 11.5, water 6.9)
	Geographic region	Australia (production of polymers in China, transport to Victoria (Australia) where the package is produced and combined with the food product, transport to Queensland (Australia) where the product is sold).	
	Life cycle stages	All (production of food consumed at the house and the associated transport and refrigeration not included in system boundaries).	
	Use phase assumptions	7.5% of beef is wasted at the household and 4% at retail	
	End of life assumptions	Landfill	
Indicators	CO_2 emissions (GWP100)	🟩	🟥
	Water use	🟩	🟥
Method	SimaPro		
Data and software	Ecoinvent version 3.2, AusLCI version 1.26, Australasian LCI version 2011.8		
Reviewed	Peer-reviewed journal article		

Comparison of bacon packaging on a life cycle basis: A case study: Kang, Sgriccia, Selke and Auras (2013)

The objective of this study was to evaluate the environmental effects of reducing the mass of traditional bacon packaging compared to substituting with new packaging material. Traditional bacon packaging consists of wax coated paper sandwiched between polyethylene layers, referred to as L-board. The new packaging material (OLB board) is primarily extruded polystyrene (XPS) joined to an oriented polypropylene (OPP) film with adhesive. Both bacon packaging boards have an overwrap pouch, made from nylon and polyethylene (PE). The following scenarios are investigated in the life cycle assessment:

- Traditional L-board packaging
- Traditional L-board packaging with a 25% mass reduction of the board
- Traditional L-board packaging with a 50% mass reduction of the board
- OLB-board packaging (EPS resin sourced from Europe)
- OLB-board packaging (EPS resin sourced in the US)

The functional unit was the packaging required to deliver 1,000 pounds of bacon in the United States (US) or 1,000 one pound packages of bacon. The study considered all life cycle stages relevant to the packaging from resource extraction, manufacturing, transport, retail and end-of-life. Due to the contamination of the packaging with bacon fat after use, recycling was not considered and the end-of-life scenario reflected US average split between landfill and incineration. The bacon packaging performed similarly in terms of giving rise to food waste (1% of bacon disposed from leaking packaging in the case of the OLB-board packaging and 2% for the L-board packaging) and given this small contribution, it was excluded from the study. It was noted, however, that light weighting of the L-board packaging may impact its structural integrity and lead to increased food waste. Table B2 summarizes the main parameters of the study and provides an overview of the results.

Summary of results and conclusions

Considering the L-board packaging, the results confirm that **light weighting reduces environmental impact proportionally.** Even so, the light weighting only applied to the board itself and not the pouch, which remained unchanged. The alternative packaging is lighter overall; the OLB-board is less than a third of the weight of the L-board, almost 25% lighter than the 50% weight reduced L-board; and the pouch is 20% lighter. **The environmental impacts for the OLB-board packaging are therefore improved across all impact categories, with the exception of mineral extraction.** This is because the packaging is now completely based on fossil resources, with EPS replacing the kraft paper in the L-board.

Table B2: Summary table: Kang *et al*. (2013)

		Products considered in study				
		Traditional (L-board) Bacon Packaging			New Light Weighted (OLB) Bacon Packaging	
		L-Board	L-Board 25	L-Board 50	OLB First	OLB Second
Study scope	Materials	Polyethylene/wax coated paper/poly-ethylene			Reverse printed oriented polypropylene/expanded polystyrene with adhesive	
	Functional unit (FU)	packages to deliver 1,000 lb of bacon to the retail consumer (1,000 bacon packages of capacity 1 lb each) in the U.S.				
	Number per FU	1,000				
	Weight [grams]	24,610	20,770	16,930	13,150	
		Board 15,450 (Paper 8,690, wax 4,400, polyethylene 2,260, ink 231)	Board 11,620 (paper 6,520, wax 3,300, polyethylene 1,700, ink 100)	Board 7,810 (paper 4,370, wax 2,210, polyethylene 1,130, ink 100)	Board 5,910 (EPS 5,270, BOPP 330, adhesive 210, ink 100)	
		Pouch 9,150 (nylon 3,030, polyethylene 6,120)	Pouch 9,150 (nylon 3,030, polyethylene 6,120)	Pouch 9,150 (nylon 3,030, polyethylene 6,120)	Pouch 7,250 (nylon 2,400, polyethylene 4,850)	
	Geographic region	U.S.			Made in the U.S. with the EPS resin produced in Dusseldorf, Germany.	Made in the U.S. with the EPS resin produced in Huston, Texas.
	Life cycle stages	Cradle-to-grave (cradle-to-cradle boundaries for corrugated boxes and PE bags)				
	End of life assumptions	81.5% Landfill, 18.5% Incineration with no energy recovery (avoided burden for the corrugated boxes and PE bags)				
Indicators	Global warming	🟥	🟨	🟨	🟩	🟩
	Acidification	🟥	🟨	🟨	🟩	🟩
	Ecotoxicity	🟥	🟨	🟨	🟩	🟩
	Carcignogenics	🟥	🟨	🟨	🟩	🟩
	Smog	🟥	🟨	🟨	🟩	🟩
	Eutrophication	🟥	🟨	🟨	🟩	🟩
	Ozone depletion	🟥	🟨	🟨	🟩	🟩
	Non carcinogenics	🟥	🟨	🟨	🟩	🟩
	Respiratory effect	🟥	🟨	🟨	🟩	🟩
	Land occupation	🟥	🟨	🟨	🟩	🟩
	Non-renewable energy	🟥	🟨	🟨	🟩	🟩
	Mineral extraction	🟨	🟨	🟩	🟥	🟥
Method	TRACI 2 and Impact 2000 + v 2.06					
Data and software	SimaPro					
Reviewed	Peer-reviewed journal article					

APPENDIX B

Life cycle assessment of food packaging and waste: Phase 2: Case study results: Heller, Cecco, Liu and Keoleian (2016)[20]

This study aimed to investigate the trade-offs in environmental impact between food waste and food packaging, and by doing so unpack the role that packaging plays in controlling food waste. The study mainly focuses on meat packaging, but also includes a comparison of lettuce packaging. For the meat packaging, two types of meat (beef and turkey), and four separate case studies were considered. The three beef case studies focus specifically on food waste at the retail level, drawing on data from retailers on actual food waste rates according to packaging type. The following types of packaging are compared for each of the beef case studies:

Case study 1a:

- 1 lb beef in a polystyrene tray with LDPE overwrap
- 1 lb beef in a modified atmosphere packaging (MAP) PP/EVOH tray.

The data from the retailer suggested that the "target" waste rates for these products are 7% and 5% respectively. Consumer waste was assumed to be independent of packaging type and set at 20%. Table B3 summarizes the main parameters and results of case study 1a.

Summary of results and conclusions: Case study 1a

This study demonstrated that the main source of GHG emissions and energy demand is the production and processing of the beef followed by the production of the packaging itself. In fact, **food production, processing and disposal accounts for between 90-97% of the total GHGE while the packaging production and disposal only accounts for around 1-2%.** The results are close between the two packaging types with the MAP tray performing marginally better in terms of GHG emissions and the PS tray having slightly lower energy demand. **When the food waste levels are similar, there is not a clear preferred packaging option**. However, if the consumer waste level is assumed to decrease due to the MAP extending shelf life on the consumer side, then the MAP performs better in terms of both indicators.

Table B3: Summary table Case study 1a: Heller *et al.* (2016)

		Products considered in study		
		Case 1a		
		1lb Beef in PS tray with overwrap	1lb Beef in hi O_2 MAP tray	
Study scope	Materials	21.3% PS, 78.4% LDPE, 0.3% paper	96% PP, 4% EVOH (and the gas is 80% O_2 and 20 CO_2).	
	Functional unit (FU)	1 kg of food consumed		
	Weight [grams]	26.8	54	
	Geographic region	USA		
	Life cycle stages	All (food losses/waste at the agricultural production stage are not explicitly considered, but will be considered for retail and consumption stages. Transportation is accounted for between major stages)		
	Use phase assumptions	20% consumer food waste	20% consumer food waste	13.6% consumer food waste
	End of life assumptions	Landfill, incineration, composting		
Indicators	GHG emissions (kg CO_2e)	🟥	🟧	🟩
	Energy demand (MJ)	🟧	🟥	🟩
Method	IPCC 2013 GWP 100a method for global warming, Ecoinvent version 2 for cumulative energy			
Data and software	Ecoinvent 3, USLCI			
Reviewed	Peer reviewed			

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[20] The fact that his study considers actual food waste rates at the retail level led to the decision to include it in the meta-analysis even though it does not fully meet the selection criteria (it considers only greenhouse gas emissions and cumulative energy).

Case study 1b:

This study included an array of beef packaging, but there were very few examples of identical products in different packaging that could be used to evaluate the impact of packaging on food waste and overall impact. Nevertheless, the case study provided other important insights in terms of the parameters that influence food waste beyond packaging. The packaging types included the following, with the retail waste rates noted in brackets:

- 80/20 fine ground beef in chub packaging LDPE/EVA/PVdC (1.07% retail waste)
- 80/20 ground chuck prepared in store in PS tray with LDPE overwrap (1.0% retail waste)
- 80/20 case ready ground beef in PS tray with LDPE overwrap (1.95% retail waste)
- Beef shank in MAP PP/EVOH tray (4.96% retail waste)
- Chuck shoulder ranch steak in PS tray with LDPE overwrap (11.85% retail waste)
- Top sirloin fillet in PS tray with LDPE overwrap (1.32% retail waste)
- Bone-in rib-eye steak in PS tray with LDPE overwrap (11.19% retail waste)

Table B4 summarizes the main parameters and results of case study 1b.

Summary of results and conclusions: Case Study 1b

In Table B4, only the first three products are directly comparable as they contain the same product. The chub or tube packaging performs best overall, most likely due to the relative amount of packaging materials together with low retail wastage rates. For the remaining products, the energy and GHG emissions follow food wastage rates, with **higher impacts seen with higher food wastage rates**. An important observation from this case study was that there are many other factors, besides packaging, that impact retail food waste. These relate to the demand for a particular product, consumer preference, product turnaround, price, as well as in-store marketing aspects. In some cases, consumers can find additional packaging more appealing.

Table B4: Summary table Case study 1b: Heller *et al.* (2016)

		Products considered in study						
		Case 1b						
		1 lb Chub packaging for 80/20 fine ground beef	1lb 80/20 in-store ground chuck, tray/overwrap	1lb case-ready 80/20 ground beef, tray/overwrap	Beef shank: hi O_2 MAP	Chuck shoulder ranch steak; tray	Top sirloin filet; tray	Bone-in ribeye; tray
Study scope	Materials	80% LDPE, 10% EVA, 10% PVdC	21.3% PS, 78.4% LDPE, 0.3% paper	21.3% PS, 78.4% LDPE, 0.3% paper	96% PP, 4% EVOH (and the gas is 80% O2 and 20 CO2).	21.3% PS, 78.4% LDPE, 0.3% paper	21.3% PS, 78.4% LDPE, 0.3% paper	21.3% PS, 78.4% LDPE, 0.3% paper
	Functional unit (FU)	1 kg of food consumed						
	Weight [grams]	11	26.8	26.8	54	26.8	26.8	26.8
	Geographic region	USA						
	Life cycle stages	All (food losses/waste at the agricultural production stage will not be explicitly considered, but will be considered for retail and consumption stages. Transportation will be accounted for between major stages)						
	Retail waste %	1.07%	1.00%	1.95%	4.86%	11.85%	1.32%	11.19%
	End of life assumptions	Landfill, incineration, composting						
Indicators	GHG emissions	🟩	🟧	🟧	🟧	🟥	🟧	🟧
	Energy demand	🟩	🟧	🟧	🟧	🟥	🟧	🟧
Method	IPCC 2013 GWP 100a method for global warming, Ecoinvent version 2 for cumulative energy							
Data and software	Ecoinvent 3, USLCI							
Reviewed	Peer reviewed							

Case study 1c:

This case study drew on data presented in a study by an Austrian consultancy, Denkstatt, which compared two types of beef packaging systems:

- Sirloin steak aged in a vacuum bag (20g per 6kg steak), packaged in EPS tray with top film (34% retail waste).
- Sirloin steak aged and packaged in multi-layer PS/ EVA/LDPE "skin" packaging (18% retail waste)

Details of the case study parameters and results are presented in Table B5.

Summary of results and conclusions: Case study 1c

For this study, the skin packaging resulted in a significant reduction of food waste at the retailer. As impacts follow food waste, the difference is seen in the environmental indicators. **Even though the skin packaging requires slightly more energy in its production, the reduction in food waste more than offsets this.** Increasing the retail food waste of the skin packaging scenario as high as 32%, will still be sufficient to break even on the energy demand of the sealed tray packaging with a retail food waste of 34%.

Table B5: Summary table Case study 1c: Heller *et al.* (2016)

		Products considered in study	
		Case 1c	
		EPS tray sealed with top film for 358 g sirloin steak	Darfresh skin packaging for a 300g sirloin steak
Study scope	Materials	2.22% PVdC, 10.82% LDPE, 2.59% EVA, 67.01% EPS, 8.23% EVOH, 8.23% PA	62% PS, 26% EVA, 125 LDPE
	Functional unit (FU)	1 kg of food consumed	
	Weight [grams]	41.9	63.3
	Geographic region	USA	
	Life cycle stages	All (food losses/waste at the agricultural production stage will not be explicitly considered, but will be considered for retail and consumption stages. Transportation will be accounted for between major stages)	
	End of life assumptions	Landfill, incineration, composting	
Indicators	GHG emissions	🟥	🟨
	Energy demand	🟥	🟨
	Retail food waste	🟥	🟨
Method	IPCC 2013 GWP 100a method for global warming, Ecoinvent version 2 for cumulative energy		
Data and software	Ecoinvent 3, USLCI		
Reviewed	Peer reviewed		

A comparative life cycle assessment of meat trays made of various packaging materials: Maga, Hiebel and Aryan (2019)

The objective of this study was to evaluate the environmental impacts of different meat trays currently in use in Europe. Due to the current drive towards a circular economy, and in particular, increased recycling targets for plastics in Europe, the focus of this study was on the impact of the end-of-life and increased recycled content of the meat trays. The life cycle stages included related to polymer production, production of additives and fillers, absorption pad production, tray production, transport and secondary packaging, recycling and end-of-life treatment. The study did not include production of meat, filling of the meat tray, sealing the meat trays, retail or use phase of the packaging and thus excluded the impact of the packaging on shelf life and resulting food waste.

The functional unit of the study was a tray with a volume of approximately 1L for preserving 500g of fresh meat. All trays allowed for the absorption of liquids released through the meat, mostly through a cellulose, super absorber and PE film absorption pad. The exception is the "open cell" extruded polystyrene (XPS), which is able to absorb liquids within the packaging material itself. Nine different types of meat packaging trays were considered:

- extruded polystyrene closed cells foam (XPS CC);
- extruded polystyrene open cells foam (XPS OC);
- extruded polystyrene with five-layer structure containing ethylene vinyl alcohol (XPS-EVOH);
- polystyrene with five-layer structure containing ethylene vinyl alcohol (PS-EVOH);
- recycled polyethylene terephthalate (rPET);
- recycled polyethylene terephthalate with polyethylene layer (rPET-PE);
- amorphous polyethylene terephthalate (APET);
- polypropylene (PP); and
- polylactic acid (PLA).

The composition of the absorption pad was assumed to be constant and comprised 64% cellulose, 10% super absorber and 26% PE film.

Summary of results and conclusions

The key study parameters and results are summarized in Table B6. Overall, the extruded polystyrene (open cell) trays have the lowest impacts across most of the impact categories considered, with PLA performing the worst. **Due to their lighter weight, all XPS trays have lower impacts than PP, PLA and PET trays for all investigated impact categories, apart from resource depletion.** In addition, multi-layer packaging has higher environmental impacts than trays made from a single material.

Table B6: Summary table: Maga, Hiebel and Aryan (2019)

		Products considered in study								
		XPS CC trays	XPS OC trays	XPS-EVOH trays	PS-EVOH trays	rPET trays	rPET-PE trays	APET trays	PP trays	PLA trays
Study scope	**Materials**	Extruded PS (closed cell)	Extruded PS (open cell)	Extruded PS with 5-layer structure containing EVOH	PS with 5-layer structure containing EVOH	Recycled PET	Recycled PET with polyethylene layer	Amorphous PET	PP	PLA
	Functional unit (FU)	A tray with a volume of about 1L for preserving 500g of fresh meat								
	Weight [grams]	6.68	9.9	9.13	13.35	18.5	18.43	9.66	11.9	13.9
		Material 6.68	Material 9.9	Material 7.97	Material 11.90	Material 18.50	Material 18.43	Material 17.65	Material 11.90	Material 13.90
		Liner 0	Liner 0	Liner 1.16	Liner 1.45	Liner 0	Liner 0	Liner 2.01	Liner 0	Liner 0
	Geographic region	Germany								
	Life cycle stages	Cradle-to-gate with end-of-life (not including production of meat, filling tray with meat, sealing the trays, or product use)								
	Use phase assumptions	Food waste was excluded in this analysis								
	End of life assumptions	75.7% Incinerated, 24.3% Landfill with energy recovery for thermal treatment			74.8% Incinerated, 25.2% Landfill with energy recovery for thermal treatment	82.7% Incinerated, 17.3% Landfill with energy recovery for thermal treatment			45.1% Incinerated, 15.3% Landfill, 39.7% Recycled with energy recovery for thermal treatment	66.8% Incinerated, 33.2% Landfill with energy recovery for thermal treatment

APPENDIX B

Table B44: Continued – Summary table: Maga, Hiebel and Aryan (2019)

		Products considered in study								
		XPS CC trays	XPS OC trays	XPS-EVOH trays	PS-EVOH trays	rPET trays	rPET-PE trays	APET trays	PP trays	PLA trays
Indicators	Acidification	🟧	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟥
	Climate change	🟩	🟧	🟧	🟧	🟧	🟧	🟥	🟧	🟧
	Eutrophication freshwater	🟧	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟥
	Eutrophication marine	🟧	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟥
	Eutrophication terrestrial	🟧	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟥
	Ionizing radiation	🟧	🟧	🟧	🟧	🟩	🟧	🟧	🟧	🟥
	Land use	🟧	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟥
	Ozone depletion	🟧	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟥
	Particulate matter	🟧	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟥
	Photochemical ozone formation	🟩	🟩	🟧	🟧	🟩	🟧	🟧	🟧	🟥
	Resource depletion (water)	🟧	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟥
	Resource depletion	🟧	🟥	🟧	🟧	🟩	🟧	🟧	🟧	🟧
Method	International Life Cycle Data Method									
Data and software	GaBi Database									
Reviewed	Peer reviewed									

The influence of packaging attributes on recycling and food waste behaviour – An environmental comparison of two packaging alternatives: Wikström, Williams and Venkatesh (2016)[21]

Historically, many food packaging LCAs have tended to focus on the direct impacts of food packaging, without considering the indirect impacts associated with recycling and food waste. Both factors are strongly influenced by consumer behaviour. This study focused on the impact of these factors on the overall performance of the packaging from a life cycle perspective. The study also looked at how the packaging types compared qualitatively in terms of the attributes that impact the ease of recycling and generation of food waste.

The two different minced meat packaging types evaluated are:

- A conventional PET tray covered with an LDPE/PET film with paper/LDPE label
- A new polyamide (PA) tube packaging sealed with aluminium clips and with an LDPE label

Table B7 summarizes the key study parameters and results. Most life cycle stages are included in the analysis, with transport and refrigeration assumed to be similar between the two packaging types and ignored. Incineration is assumed to off-set the fuel requirements of a typical co-generation plant in Europe. The fraction recycled was considered the most uncertain parameter and so this factor was varied between 0 and 100%.

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[21] The relatively few studies focussing on food waste and end-of-life (recycling) led to the decision to include this study in the meta- analysis even though it does not fully meet the selection criteria (it considers only global warming, acidification and ozone depletion).

Summary of results and conclusions

If food waste is not included in the analysis, then the lighter tube packaging performs slightly better across all impact categories assessed. Complete material recycling of both packaging materials provides additional benefit. However, the authors note that although seemingly better from an initial assessment of direct impacts, the tube packaging has attributes that make food waste unavoidable. As well as being difficult to empty completely, the tube packaging is difficult and time-consuming to separate (i.e. remove the metal clips) and clean thoroughly. Therefore, it is **more likely that the tube packaging will be disposed in the unsorted waste fraction** and, in this country context, be incinerated. The tray packaging in contrast allows the meat product to be easily removed without leaving any food waste behind. It is also easier to clean. It was noted, however, that consumers generally have an aversion to handling meat packaging, which may influence recycling rates.

Table B7: Summary table: Wikström, Williams, and Venkatesh (2016)

		Products considered in study					
		Tube packaging				Tray packaging	
		Excluding food loss		Including food loss			
Study scope	**Materials**	Polyamide, aluminium, LDPE				PET, LDPE, paper	
	Functional unit (FU)	1 kg of eaten minced meat					
	Number per FU	2.00		2.04		1.97	
	Weight [grams]	505.85				529.15	
		Plastic sheet 3.3				Tray 18.2	
		Clips 1.1				Film 1.79	
		Label 1.45				Plastic label 0.66	
		Minced meat 500				Paper label 0.5	
						Minced meat 508	
	Geographic region	Sweden					
	Life cycle stages	Cradle-to-farm-gate (not including intermediate transport or storage and refrigeration), end-of-life for packaging and food waste					
	End of life assumptions	The study considers all scenarios from 0%–100% of the packaging recycled, with food waste and non-recycled packaging incinerated for energy recovery.					
		0% recycling	100% recycling	0% recycling	100% recycling	0% recycling	100% recycling
Indicators	GHG emissions	🟧	🟩	🟥	🟧	🟧	🟧
	Acidification	🟩	🟩	🟥	🟥	🟧	🟧
	Ozone	🟩	🟩	🟥	🟥	🟧	🟧
Method	SimaPro						
Data and software	Ecoinvent 3, ELCD						
Reviewed	Peer reviewed						

B.1.2 Dairy and dairy substitutes

Environmental impact of biodegradable food packaging when considering food waste: Dilkes-Hoffman *et al.* (2018)[22]

The premise of this paper is that biodegradable plastic packaging has a role to play in replacing conventional multi-layer plastic packaging that is non-recyclable and non-degradable. This is in recognition of the fact that most plastic food packaging is not suitable for recycling and has limited waste management options available to it. The study focuses specifically on the GHG trade-offs between the following types of packaging for beef and cheese:

- traditional polypropylene (PP) packaging and
- biodegradable packaging made of thermoplastic starch (TSH) and polyhydroxyalkanoate (PHA).

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[22] The relatively few studies considering bio-based and biodegradable plastics led to the decision to include this study in the meta-analysis even though it does not fully meet the selection criteria (it considers only greenhouse gas emissions and water use).

APPENDIX B

TSH and PHA were selected as together they provide the same functionality as conventional multi-layer plastic packaging: TSH is considered to have the best oxygen barrier properties of all polymeric materials and PHA the best water barrier properties out of all biodegradable polymers. In addition, both these polymers are seen to degrade in sea water, and therefore likely to have lower impacts on marine environments than conventional plastics. The life cycle included the portion of food waste generated, but not the fraction of food consumed. The default end-of-life assumption for both the food and the packaging was landfill with no methane capture. Alternative end-of-life scenarios investigated were landfill with methane capture, composting and anaerobic digestion for the bio-based and biodegradable plastic packaging and food waste. The study parameters and results for cheese are summarized in Table B8.

Summary of results and conclusions

This study shows that for cheese, **the impacts of the food waste are not as significant as for other high emissions intensive foods and is comparable to the impacts associated with the packaging.** Direct comparison of the packaging types showed that there is little difference in the packaging production phases between the two types of polymers (conventional and bio-based). However, the impacts associated with bio-based polymer production show a much wider range due to the variability associated with the feedstock and production method. Similarly, the end-of-life assumptions significantly affect the overall bio-based packaging GHG emissions. When bio-based plastics are sent to landfill they can degrade and release methane. In contrast, fossil-based plastics are largely inert. If landfill gas capture is included, then the emissions associated with the end-of-life of bio-based plastics would be substantially reduced.

The study concludes that bio-based packaging may have a role to play when it can be co-disposed with food waste thus reducing landfill emissions associated with both the food and the packaging. However, for the bio-based packaging to outperform the PP packaging, it would need to also be associated with a significant reduction in food waste.

Table B8: Summary table: Dilkes-Hoffman *et al*. (2018)

		Products considered in study	
		PP Package	**PHA-TPS Package**
		Cheese	**Cheese**
Study scope	Materials	Polypropylene	Thermoplastic starch, PHA
	Functional unit (FU)	1 kg of packaged product at the house	
	Weight [grams]	58	58
		-	PHA 11.6, starch 27.8, glycerol 11.6, water 7
	Geographic region	Australia (production of polymers in China, transport to Victoria (Australia) where the package is produced and combined with the food product, transport to Queensland (Australia) where the product is sold).	
	Life cycle stages	All (production of food consumed at the house and the associated transport and refrigeration not included in system boundaries).	
	Use phase assumptions	5% of cheese is wasted at the household and 4.5% at retail	
	End of life assumptions	Landfill	
Indicators	CO$_2$ emissions (GWP100)	🟩	🟥
	Water use	🟩	🟥
Method	SimaPro		
Data and software	Ecoinvent version 3.2, AusLCI version 1.26, Australasian LCI version 2011.8		
Reviewed	Peer reviewed		

Role of Packaging in LCAs of Food Products: Silvenius *et al*. (2011)[23]

This study is one of the few to consider the full life cycle of the food packaging as well of the food itself. This is to understand the contribution of food packaging to the overall environmental impact of the product and to investigate the role of food waste. The study is unique in that it uses survey data to determine the food wastage rates in households, with a particular focus on the impact of different size packaging. One of the food products considered is soygurt packaging. Soygurt is a soy-based yoghurt like product. Two alternative packaging types were considered:

- 750ml liquid packaging board (LPB) with aluminium barrier
- 150ml polypropylene cup with aluminium cover

Table B9 summarizes the main parameters of the study and provides an overview of the results. The functional unit of the study is 1000 kg of food consumed. The study considered all life cycle stages, from the manufacture of raw materials used in packaging, through to the end-of-life management of the packaging and material recovery. The impacts associated with the food waste were also included, with three different levels of food waste investigated for each packaging type based on consumer surveys. Four different scenarios were included for waste management. Two scenarios reflected currently applied waste management situations with a split between landfill, material recovery with and without energy recovery. The remaining two scenarios considered future possible waste management splits: one where energy recovery is maximized over landfilling and material recovery; and one where material recovery is maximized with the remaining waste used for energy recovery. In the assessment avoided emissions were included for the composting and energy recovery. Composting of bio-based materials was assumed to avoid peat production for soil enrichment and energy recovery avoided the use of natural gas for heating. For recycling, an open allocation method was applied. The LCA only considered three impact categories, namely climate change, eutrophication and acidification. However, the paper only presented results graphically for climate change impacts.

Summary of results and conclusions

The study found that for soygurt, packaging production made up between 5 and 6% of the total climate change impact in the case of the LPB, but between 10 and 13% in the case of PP cups. Depending on the degree of food waste, the contribution to overall climate change impact was comparable to the packaging impact in the case of the LPB at between 5 and 11%, while for the PP cup the contribution of food waste was lower than the packaging impact at only between 2 and 6%. This is due to the ratio of packaging to food being higher for the smaller portion PP cup than for the LPB. The reason that food waste was less significant for this food type was due to the high water content associated with the food.

The climate change impacts associated with waste management varied depending on the fate of packaging materials and food waste. If the food waste was sent to landfill the climate impacts were high due to the release of methane, whereas if the food waste was disposed of down the drain, the impacts associated with wastewater treatment were much lower. Similarly, if the LPB was sent to landfill rather than energy recovery or material recovery, the climate impacts were much higher due to the generation of methane in landfills. Thus**, for the waste management scenario where landfilling is significant** (Scenario 1)**, the LPB impacts are comparable to (or higher than) the PP cup,** depending on the level of food waste in each packaging type. **For all other waste management scenarios the LPB packaging performed better than the smaller PP cup.**

A further finding of the study was that consumers have difficulty in estimating how much food they waste, which is a critical parameter for studies such as this, particularly for foods where the packaging impact is small compared to the food waste impact.

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[23] The fact that this study is the only one to include a consideration of household-level food waste led to the decision to include it in the meta-analysis despite it considering only carbon footprint.

APPENDIX B

Table B9: Summary table: Silvenius *et al.* (2011)

		Products considered in the study	
		Liquid packaging board	**PP cup**
Study scope	Materials	Liquid packaging board with alumnium barrier (asceptic brick shaped package)	Polypropylene cup with aluminium cover
	Functional unit (FU)	1000 kg of food consumed	
	Number per FU	Not reported, but varies according to consumer food waste rates	
	Weight [grams]	23 g	6 g
	Geographic region	Soybeans used in the production of Soygurt were cultivated in Ohio, USA. Blueberries for soyghurt were imported from South-East Asia. All products produced and consumed in Finland.	
	Life cycle stages	All	
	Use phase assumptions	5, 8 and 11% food waste	2, 4, and 6% food waste
	End of life assumptions	Scenario 1: Average metropolitan area waste management rates: landfill, material recovery, no energy recovery Scenario 2: Average metropolitan area waste management rates: landfill, material recovery, energy recovery from mixed plastics Scenario 3: Future waste management with energy recovery maximized over material recovery and landfilling Scenario 4: Future waste management with material recovery for fibre and plastics with remainder sent to energy recovery	
Indicators	Scenario 1: Climate change	🟧	🟧
	Scenario 2: Climate change	🟩	🟥
	Scenario 3: Climate change	🟩	🟥
	Scenario 4: Climate change	🟩	🟥
Method	ISO/TR 14049, Environmental management–Life cycle assessment		
Data and software	Ecoinvent, Finnish national quality database, Information Centre of the Ministry of Agriculture and Forestry database.		
Reviewed	Book chapter–reviewed by editors of book.		

Plastic or Glass: A New Environmental Assessment with a Marine Litter Indicator for the Comparison of Pasteurized Milk Bottles: Stefanini, R., Borghesi, G., Ronzano, A. and Vignali, G. (2021)

The aim of this study was to compare the life cycle environmental impacts of bottles made of PET, rPET, non-returnable glass and returnable glass in order to identify the most environmentally preferable packaging solution. The comparison is carried out on the PET, R-PET, glass and returnable glass bottles used to package 1 litre of pasteurized milk, taking into account the production, transport and disposal of the bottles. Inventory data was provided by a milk processing and packaging factory in Italy. A marine litter indicator was developed for the study and applied along with selected impact categories of the ReCiPe 2016 impact assessment method. Table B10 summarizes the key study parameters and results.

Summary of results and conclusions

The rPET bottle has the lowest potential contribution to global warming, stratospheric ozone depletion, terrestrial acidification, fossil resource scarcity, water consumption and human carcinogenic toxicity, followed by the PET bottle, the returnable glass bottle, and finally the single-use glass bottle. Glass is the least preferred packaging option because of high energy use in bottle production and higher transport phase emissions as a result of its higher weight. **Returnable glass bottles are preferred to single-use glass bottles, but at eight reuses, the PET and rPET bottles have lower impacts than the returnable glass bottles.** However, the returnable glass bottles are the best performing option against the Marine Litter Indicator.

Table B10: Summary table: Stefanini *et al*. (2021)

		Bottles considered in study			
		PET	**rPET**	**Glass (single-use)**	**Returnable glass**
Study scope	Materials	PET bottle, HDPE cap	50% recycled PET bottle, HDPE cap	62.5% recycled white glass bottle, steel cap	62.5% recycled white glass bottle, steel cap
	Functional unit (FU)	A container for 1 litre of pasteurized milk considering the bottle, the cap and the label, and all the activities and materials connected to the packaging activities			
	Number per FU	1	1	1	0.125
	Weight [grams]	22 g (bottle); 2.68 g (cap)	22 g (bottle); 2.68 g (cap)	400 g (bottle); 3.43 g (cap)	400 g (bottle); 3.43 g (cap)
	Geographic region	Italy			
	Life cycle stages	Cradle to grave (extraction of packaging raw materials, manufacturing of packaging, production (sterilizing, filling and packaging), end of life, as well as transport activities). Milk production is not included.			
	Use phase assumptions	N/A			8 uses, i.e. 7 cycles of reuse, including transport to collection centre, transport from collection centre to food companies, washing, new cap, new label, and new auxiliary materials.
	End of life assumptions	Recycling, landfill and incineration with energy recovery (material percentages applicable to Italy)			
Indicators	GWP (kg CO$_2$ eq)	🟧	🟩	🟥	🟧
	Ozone depletion potential (kg CFC$_{11}$ eq)	🟩	🟩	🟥	🟧
	Terrestrial acidification (kg SO$_2$ eq)	🟧	🟩	🟥	🟧
	Fossil resource scarcity (kg oil eq)	🟧	🟩	🟥	🟧
	Water consumption (M^3)	🟧	🟩	🟥	🟧
	Human carcinogenic toxicity (kg 1.4-DCB)	🟧	🟩	🟥	🟧
	Marine litter indicator	🟧	🟧	🟥	🟩
Method	ReCiPe 2016 MidPoint (H) method and a marine litter indicator (MLI)				
Data and software	ecoinvent 3.5 database and SimaPro 9.0				
Reviewed	Peer-reviewed journal				

APPENDIX B

The influence of packaging attributes on consumer behaviour in food packaging life cycle assessment studies – A neglected topic: Wikström, Williams, Verghese and Clune (2014)[24]

The purpose of this study was to demonstrate the impact of including food waste on the outcomes of a life cycle assessment of food packaging. The premise is that if food waste is ignored a life cycle assessment could show a preference for a lighter packaging which may have a higher overall impact if food waste was considered. The study considered the packaging attributes that contributed to the avoidance of food waste, namely: "contains the correct quantity" and "easy to dose". For yoghurt packaging, the available packaging types varied considerably in terms of these attributes. Yoghurt was also selected as a case study as in Australia it was found to have high wastage rates of approximately 12%, attributed to the typically large size of containers and the contents were not finished before the sell by date.

Three different size yoghurt packaging types were included in the analysis to determine the impact of different portion sizes and packaging types on global warming:

- A 70g laminate pouch (PE, Aluminium and PP)
- A 6-pack of 175g connected tubs (PS)
- A 900g PP and aluminium tub

Table B11 summarizes the key study parameters and results. The study included food waste, which was assumed at 5, 12 and 20%. Different extremes of waste management was considered for the packaging – either 100% recycling or 100% incineration (without energy recovery). Food waste was assumed to be industrially composted. The study only considered the impact on global warming potential.

Summary of results and conclusions

This study shows that for this food type, food waste has less of an influencing factor on global warming potential than for other more emissions intensive food types. In general, overall emissions were lower with high recycling rates than for incineration across all packaging types. The pouch, if incinerated, had the worst performance, with the connected tubs performing slightly better than the other two packaging types with recycling if food wastage rates were comparable. The **results were close, with no clear packaging preference across all food wastage rates.**

Table B11: Summary table: Wikström *et al*. (2014)

		Products considered in study					
		Yoghurt Packaging					
		70 g Laminate pouch		6 Pack of 175 g connected tubs		900 g tub	
Study scope	Materials	PE, Aluminium and PP		PS		PP and Aluminium	
	Functional unit (FU)	1 kg eaten mince meat					
	Weight [grams]	6		42		37	
		PE + aluminium 2				PP 35	
		PP 4				Aluminium 2	
	Geographic region	Sweden					
	Life cycle stages	All (packaging raw material production to final disposal, including production and disposal of food product)					
	End of life assumptions	100% Recycling	100% Incineration without energy credits	100% Recycling	100% Incineration without energy credits	100% Recycling	100% Incineration without energy credits
Indicators	Global warming potential						
Method	PIQET for packaging system specifications and SimaPro for LCA						
Data and software	SimaPro						
Reviewed	Peer-reviewed journal article						

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[24] The relatively few studies considering food waste led to the decision to include this study in the meta-analysis despite it considering only carbon footprint.

B.1.3 Refrigerated prepared foods

Food losses, shelf life extension and environmental impact of a packaged cheesecake: A life cycle assessment: Gutierrez, Meleddu and Piga (2017)

The study investigates the role of packaging in maintaining food quality, improving shelf life and waste disposal of the container and food waste. By considering how the shelf life of these food products can be improved through their packaging, less wastage will be created as there will be a larger selling window for the food products. The study aims to recognise improved food packaging solutions that minimize environmental impact and maximize economic sustainability. The economic sustainability is contributed to by improved shelf life of the food products, which has some dependency on the type of packaging used. Two cheesecakes were added to each of the containers, resulting in different shelf lives for each of them.

- The first type of packaging were the control samples packaged in a gas barrier recycled polyethylene terephthalate (XrPET) tray wrapped in an XrPET film, whose shelf life was seven days.
- The second container was one with a Modified Atmosphere Packaging (MAP) approach. The MAP approach includes an AerPack container with the tray made of EVOH/PS/PE gas barrier trays wrapped with a multi-layer gas and water barrier film.

The functional unit for the study was a tray containing two cheesecakes with a total weight of approximately 300g. The life cycle stages were cradle-to-gate and included the following phases: production of raw materials employed in food and packaging production, food and packaging manufacture, packaging of a tray containing two cheesecakes, logistics system, transport to retail and disposal of food and packaging. Table B12 summarizes the key study parameters and results.

Summary of results and conclusions

When the two packaging types are compared without considering shelf life extension they perform similarly across all impact categories, with the Aerpack packaging impacts between 1 and 4% lower than the XrPET packaging. **If the impact of shelf life is included in the assessment, the Aerpack packaging outperforms the XrPET packaging by between 17% and 62%.** For this food type, the impact of the food itself dominates the overall assessment, with food loss also being significant, followed by distribution.

Changing the packaging to increase shelf life has better economic and environmental sustainability as it minimizes transport costs and contributes to economic benefits by promoting more sales as the products have a larger sales window due to their increased shelf life.

Image: Cheesecake slice inside plastic container. (FotografiaBasica, iStockphoto.com)

Table B12: Summary table: Gutierrez, Meludda and Piga (2017)

		Products considered in study	
		XrPET cheesecake tray	AerPack cheesecake tray
Study scope	**Materials**	XrPET	EVOH/PS/PE, EVOH/OPET/PE, gas mixture (N_2/O_2)
	Functional unit (FU)	A tray containing two cheesecakes, with a total weight of 300g. The shelf life is 7 days.	A tray containing two cheesecakes, with a total weight of 300g. The shelf life is 28 days.
	Weight [grams]	17.45	13.54
		Tray 16	Tray 11.25
		Film 1.45	Film 2.25
		-	Gas mixture 0.035
	Geographic region	Italy	
	Life cycle stages	Raw material production to final disposal, including disposal of food losses	
	End of life assumptions	Food waste is incinerated and the plastic trays are recycled.	
Indicators	Climate change human health	🟥	🟩
	Ozone depletion	🟥	🟩
	Human toxicity	🟥	🟩
	Photochemical oxidant formation	🟥	🟩
	Particulate matter formation	🟥	🟩
	Ionising radiation	🟥	🟩
	Climate change ecosystems	🟥	🟩
	Terrestrial acidification	🟥	🟩
	Freshwater eutrophication	🟥	🟩
	Terrestrial ecotoxicity	🟥	🟩
	Freshwater ecotoxicity	🟥	🟩
	Marine ecotoxicity	🟥	🟩
	Agricultural land occupation	🟥	🟩
	Urban land occupation	🟥	🟩
	Natural land transformation	🟥	🟩
	Metal depletion	🟥	🟩
	Fossil depletion	🟥	🟩
Method	ReCiPe		
Data and software	Primary data, Ecoinvent v 3.1 database, Agri Footprint v 1.0 database, SimaPro version 8.05.13		
Reviewed	Peer reviewed		

B.2 FRESH PRODUCE

B.2.1 Ready-to-eat fresh fruits and vegetables

Evaluation of physiochemical/microbial properties and life cycle assessment (LCA) of PLA-based nanocomposite active packaging: Lorite *et al*. (2017)

This aim of this study was to assess novel PLA-nanocomposites (composed of PLA, nanoclays and surfactants) in comparison to conventional PET packaging for fresh cut melons. The PLA-nanocomposite is designed to improve the protection, and potentially the shelf life, of the cut melon. Three PLA options are compared to PET based on scenarios looking at improved shelf life (including associated food waste reductions), as well as current and desired end-of-life treatment scenarios. The three PLA options considered are:

- PLA with nanoclay,
- PLA with nanoclay and surfactant, and
- PLA with nanowhiskers and surfactant.

Prior to completing the LCA study, the performance of packaging in keeping cut melons fresh was assessed using both physiochemical analyses and microbiological assays. These results were used to guide the improved shelf life and reduced food waste scenarios considered in the LCA study.

The functional unit was the provision of 100,000 kg of fresh cut fruit to customers, including food loss that occurs prior to the consumer. The system boundaries covered cradle-to-grave impacts and therefore included raw material extraction/production, plastic production, packaging formation, filling and end-of-life management. Retail and use phases were assumed equivalent between the systems and were excluded from the analysis. All modelling and impact assessment was conducted in SimaPro using the IMPACT2002+ v2.11 impact assessment methodology, along with the bulk waste impact category from the EDIP 2003 methodology.

The key study parameters and results are summarized in Table B13.

Summary of results and conclusions

The PET packaging had reduced impacts in most of the impact categories considered, which is primarily attributed to the high energy demand for PLA manufacturing and mixing of the additives into the PLA polymer. This particularly results in PLA having higher global warming impacts than PET. The bio-based nature of PLA results in it having lower human health impacts than PET but larger ecosystem impacts than the fossil fuel-derived polymer.

The potential shelf life extension associated with the use of the novel active packaging was investigated using scenarios. This showed that **if the shelf life was extended by 30% (i.e. from 15 days to 20 days), then the PLA packaging with nanoclays would have equal or improved environmental impacts when compared with the PET packaging.** End-of-life management was also investigated with scenarios. With current waste management, PET packaging has slightly lower overall environmental impacts associated with waste. However, if waste management shifts to the desired scenario (100% of PET incinerated and 100% of PLA composted), then PLA packaging has lower overall environmental impacts associated with waste management. Waste management impacts are however relatively small in comparison to material production and transportation, meaning that these changes do not impact the overall results.

APPENDIX B

Table B13: Summary table: Lorite *et al.* (2017)

Products considered in study					
		PLA with nanocaly	PLA with nanoclay and surfactant	PLA with nanowhiskers and surfactant	PET
Study scope	**Functional unit (FU)**	100,000 kg of fresh cut fruit to customers			
	Weight [kg]	8.34 g per package (unknown number required to fulfil functional unit			
	Geographic region	Europe			
	Life cycle stages	Cradle-to-grave excluding retail and use stages			
	Use phase assumptions	Use phase not considered			
	End-of-life assumptions	PLA: 20% composted, 40% incinerated & 40% landfilled			PET: 60% incinerated & 40% landfilled
Indicators (normalized)	**Carcinogens**	🟧	🟧	🟧	🟥
	Non-carcinogens	🟧	🟧	🟧	🟧
	Respiratory inorganics	🟧	🟧	🟥	🟩
	Terrestrial ecotoxicity	🟧	🟧	🟧	🟧
	Terrestrial acidification	🟧	🟧	🟧	🟧
	Land occupation	🟧	🟧	🟧	🟧
	Global warming	🟧	🟧	🟥	🟩
	Non-renewable energy	🟧	🟧	🟥	🟩
Method	IMPACT2002+ v2.11, with bulk waste from EDIP 2003				
Data and software	SimaPro, using ecoinvent 3				
Reviewed	Peer reviewed journal article				

Sustainability Analysis of Active Packaging for the Fresh Cut Vegetable Industry by Means of Attributional & Consequential Life Cycle Assessment: Vigil *et al.* (2020)

The aim of this study was to assess PP and PLA films coated with zinc oxide (ZnO) bactericidal nanoparticles in comparison to PP films for fresh cut products. Zinc oxide nanoparticles are of particular interest as an antimicrobial compound, as in addition to the antimicrobial properties, the particles are naturally white, can be utilized in various polymers and block UV light. The three film options were assessed using both attributional and consequential LCA systems in order to ensure that the impacts of packaging production, packaging end-of-life and food waste (i.e. background fresh cut produce production and processing linked with food wastage) were all considered. End-of-life for each film type was modelled based on alternatives currently available for municipal waste management, namely:

- PP film: 36% incineration, 30% landfill disposal & 34% recycling
- ZnO coated PP film: 50% incineration & 50% landfill disposal
- ZnO coated PLA film: 100% industrial composting

For the attributional LCA, the functional unit was the packaging to contain 130 g of fresh cut lettuce, equivalent to 3.94 grams of packaging film. The system boundaries covered cradle-to-grave impacts and therefore included raw material extraction/production, plastic production, film production and end-of-life packaging management. Filling, retail and use phases were excluded from the attributional LCA system.

For the consequential LCA, the functional unit was the packaging to contain 130 g of fresh cut lettuce ingested by a consumer. As with the attributional LCA, the system boundaries covered cradle-to-grave impacts (raw material extraction/production, plastic production, film production and end-of-life management); however, the consequential system boundaries also include food waste and the management of this waste. As such, the system includes lettuce production, lettuce processing and the disposal of any food waste (lettuce and packaging waste). As with the attributional LCA, the filling, retail and use phases were excluded from the system. Furthermore, distribution of the packaged lettuce was excluded from the consequential LCA due to the variability of this phase.

All modelling and impact assessment was conducted in SimaPro using the ReCiPe 2008 impact assessment methodology. Impacts were therefore reported against 18 midpoint, 3 endpoint impact categories and an aggregated single-score endpoint indicator. The single-score was calculated as a weighted sum of the normalized midpoint impacts. In all cases Monte Carlo analysis was performed to determine the certainty of results.

The key study parameters and results are summarized in Table B14 and Table B15 for the attributional and consequential LCAs respectively.

Summary of results and conclusions

The **attributional LCA** showed that **both ZnO coated films had improved impacts when compared with traditional PP films.** Both ZnO coated films had reduced impacts in 14 of the 18 midpoint impact categories and when considering the Monte Carlo analyses (i.e. considering only when at least 60% of iterations showed reduced impacts), the ZnO coated PLA and PP had reduced impacts in 10 and 11 of the midpoint categories respectively. This translated to the single-score result, which also indicated that both ZnO coated films resulted in lower environmental impacts than the PP film. The lower impacts of the ZnO coated PLA film is primarily due to the lower impacts of PLA manufacturing. These low impacts are a result of the maize starch feedstock for PLA production being considered an agricultural waste product and therefore having zero input burdens. It was noted by the authors that impacts, such as land occupation, would increase to levels similar to or above those of PP film if maize starch was not considered a waste product.

The **consequential LCA** also showed that both ZnO coated films had improved impacts when compared with traditional PP films. Overall, both ZnO coated films had reduced impacts in all 18 midpoint impact categories and when considering the Monte Carlo analyses, these impact reductions were significant in 13 and 11 of the midpoint categories for the ZnO coated PLA and PP respectively. Similar to the attributional LCA results, both ZnO coated films resulted in a lower single-score impact than the PP film, with the ZnO coated PLA film showing the lowest impacts overall. The analysis showed that impacts are primarily due to agricultural production of the lettuce, with the extended shelf life of the ZnO coated films resulting in less food waste and a consequential lowering of environmental impacts. The **impacts from agricultural production far outweigh the impacts from packaging end-of-life management and therefore packaging design should prioritize extending shelf life and reducing food waste** rather than optimising end-of-life treatment methods.

Image: Fresh starfuits at market stall wrapped in plastic film. (Kandl, iStockphoto.com)

Table B14: Summary table: Vigil *et al.* (2020) – Attributional LCA

		Products considered in study		
		PP	ZnO coated PP	ZnO coated PLA
Study scope	**Functional unit (FU)**	Film bag for 130 g of fresh cut lettuce		
	Weight [kg]	3.94 g of film		
	Geographic region	Global utilising Italian background data and end-of-life scenarios		
	Life cycle stages	Attributional cradle-to-grave (not including filling, retail or use)		
	End-of-life assumptions	36% incinerated, 30% landfilled, and 34% recycled	50% incinerated & 50% landfilled	100% composted
Indicators	**Water depletion**	🟥	🟧	🟧
	Urban land occupation	🟧	🟧	🟥
	Terrestrial ecotoxicity	🟧	🟥	🟧
	Terrestrial acidification	🟥	🟧	🟧
	Photochemical oxidant formation	🟥	🟧	🟩
	Particulate matter formation	🟥	🟧	🟧
	Ozone depletion	🟥	🟧	🟧
	Natural land transformation	🟥	🟧	🟧
	Metal depletion	🟧	🟥	🟧
	Marine eutrophication	🟥	🟧	🟧
	Marine ecotoxicity	🟥	🟧	🟩
	Ionising radiation	🟥	🟧	🟩
	Human toxicity	🟥	🟥	🟧
	Freshwater eutrophication	🟧	🟧	🟧
	Freshwater ecotoxicity	🟥	🟧	🟩
	Fossil depletion			
	Climate change			
	Agricultural land occupation			
	Single score			
Method	ReCiPe			
Data and software	SimaPro v8, using ecoinvent v3.2, along with data from the CEREAL project			
Reviewed	Peer reviewed journal article			

Table B15: Summary table: Vigil *et al*. (2020) – Consequential LCA

		Products considered in study		
		PP	ZnO coated PP	ZnO coated PLA
Study scope	**Functional unit (FU)**	Film bag for 130 g of fresh cut lettuce ingested by consumers		
	Weight [kg]	3.94 g of film plus film lost due to food waste within system		
	Geographic region	Global utilising Italian background data and end-of-life scenarios		
	Life cycle stages	Consequential cradle-to-grave (not including filling, retail, distribution or use) Food production and loss considered as part of the consequential system		
	End-of-life assumptions	36% incinerated, 30% landfilled, and 34% recycled	50% incinerated & 50% landfilled	100% composted
Indicators	**Water depletion**	🟥	🟨	🟨
	Urban land occupation	🟥	🟨	🟨
	Terrestrial ecotoxicity	🟥	🟨	🟨
	Terrestrial acidification	🟥	🟨	🟨
	Photochemical oxidant formation	🟥	🟨	🟨
	Particulate matter formation	🟥	🟨	🟨
	Ozone depletion	🟥	🟨	🟨
	Natural land transformation	🟥	🟨	🟨
	Metal depletion	🟨	🟨	🟨
	Marine eutrophication	🟥	🟨	🟨
	Marine ecotoxicity	🟥	🟨	🟨
	Ionising radiation	🟥	🟨	🟩
	Human toxicity	🟥	🟨	🟨
	Freshwater eutrophication	🟥	🟨	🟨
	Freshwater ecotoxicity	🟥	🟨	🟨
	Fossil depletion	🟥	🟨	🟨
	Climate change	🟥	🟨	🟨
	Agricultural land occupation	🟥	🟨	🟨
	Single score	🟥	🟨	🟩
Method	ReCiPe			
Data and software	SimaPro v8, using ecoinvent v3.2, along with data from the CEREAL project			
Reviewed	Peer reviewed journal article			

B.2.2 Whole fruit and vegetables

Comparative Life Cycle Assessment Report of Food Packaging Products: Belley (2011)

A comparative life cycle assessment of the various materials used to manufacture fruit and vegetable trays sold in Quebec was commissioned by the Cascades Specialty Product Group, Consumer Product Packaging (CSPG, CPP). The study was carried out by the Interuniversity Research Centre for the Life Cycle of Product, Processes and Services (CIRAIG). Seven packaging materials were covered in the study:

- 100% virgin extruded polystyrene foam (XPS)
- 90% virgin and 10% recycled oriented polystyrene (OPS)
- 90% virgin and 10% recycled polylactide polymer (PLA)
- 90% virgin and 10% recycled polypropylene (PP)
- 100% recycled moulded pulp

Table B16 summarizes the main parameters of the study and provides an overview of the results The functional unit chosen for the assessment was to contain and permit the stacking and retailing of the amount of fruits or vegetables that can be contained in a tray volume of 52 cubic inches to consumer in Québec in 2010. The whole life cycle of the trays is considered (production, distribution and end-of-life of the trays). No recycling credits are assigned for recycling or recovery. Instead, the environmental impacts of material recovery are allocated as the economic costs are allocated to the material, i.e. the environmental impacts of collection and recycling processes are entirely allocated to the user of the materials. Average recycling rates for Quebec are applied, with trays not assumed to be recycled, sent to landfill.

Summary of results and conclusions

The **XPS and moulded pulp trays have the lowest environmental impacts across all impact categories.** The PLA tray has the highest potential impacts across the greatest number of impact categories.

Over the life cycle of the trays, the production of the trays (including the production of their raw materials and energy used in their production) is the main contributor to all impacts categories. The main reason for the much lower impacts of the XPS tray relative to the other plastic trays is its mass, which is up to 62% lower than the other plastic trays. The main reasons for good environmental results of the moulded pulp trays are the fact that it is made from recycled materials (i.e. the only impacts associated with its materials are those arising from the collection and pulping of newspapers). The energy required in the forming of the moulded pulp trays is also relatively low compared to the plastic trays. The rPET tray has similarly low burdens associated with its materials, but this is off-set by the relatively high impacts from the forming of the comparatively heavy rPET trays.

A rigorous set of sensitivity analyses, data quality assessment, completeness and consistency checks allow **a high degree of confidence in the preference for the XPS and moulded pulp trays**. Sensitivity analyses were carried out on tray weight, the PET recycling process, the allocation approach, a change in electricity grid mix, the impact assessment method and the tray distribution distance. The overall, the conclusion of the LCA are robust, with XPS and moulded pulp trays having the lowest potential impacts across all the sensitivity analyses. The most important parameter affecting the performance of the XPS and moulded pulp trays is the weight of the tray. The tray systems are also very sensitive to the electricity grid mix used in manufacturing the trays. A change from the North American to Quebec grid mix especially benefits the environmental performance of the PLA tray.

Image: Fresh mushrooms in packaging. (4nadia, iStockphoto.com)

Table B16: Summary table: Belley (2011)

		Products considered in study						
		XPS tray	OPS tray	PET tray	rPET tray	PLA tray	PP tray	Moulded pulp tray
Study scope	**Materials**	100% virgin extruded polystyrene foam (XPS)	90% virgin-10% recycled oriented polystyrene (OPS)	90% virgin-10% recycled PET (rPET)	100% recycled PET	90% virgin-10% recycled polylactide (PLA)	90% virgin-10% recycled PP	100% recycled moulded pulp
	Functional unit (FU)	Contain and permit the stacking and retailing of an amount of fruits or vegetables that can be contained in a tray volume of 52 cubic inches to consumers in Quebec in 2010						
	Number per FU	one tray						
	Weight [grams]	10.45	20.85	27.15	27.15	25.2	19.8	20
	Geographic region	Quebec						
	Life cycle stages	All processes involved in the production, distribution and end-of-life of the trays. Transport packaging is included. All trays are packed in corrugated cardboard boxes, other than the XPS trays, which are packed in a plastic bag.						
	End of life assumptions	Average recycling rates assumed: 0% for XPS, 15% for OPS, 38% for PET and rPET, 17% for PP, 0% for PLA, 41% for moulded pulp trays and 56% of corrugated cardboard. The balance assumed to be landfilled.						
Indicators	Human health	🟩	🟩	🟥	🟩	🟥	🟧	🟩
	Ecosystem quality	🟧	🟧	🟧	🟧	🟥	🟧	🟧
	Climate change	🟩	🟥	🟥	🟧	🟥	🟥	🟩
	Resource depletion	🟩	🟥	🟥	🟧	🟥	🟥	🟩
	Aquatic acidification	🟩	🟧	🟧	🟧	🟥	🟥	🟩
	Aquatic eutrophication	🟩	🟩	🟧	🟥	🟥	🟧	🟩
Method	IMPACT 2002+							
Data and software	Primary data (specific to the packaging options) and ecoinvent available in SimaPro							
Reviewed	ISO compliant and reviewed by a four-person expert panel							

Evaluating the Environmental Impacts of Packaging Fresh Tomatoes Using Life-Cycle Thinking and Assessment: Stevenson *et al.* (2010)[25]

The aim of this demonstration project was to evaluate the direct environmental impacts of packaging options for fresh tomatoes in the USA, as well as the impact of packaging decisions on the environmental impacts of the packaged product. Thus, the study quantifies the environmental impacts associated with three tomato packaging options, but also assesses the effect of the three packaging options on the life cycle impacts of growing, transporting and retailing the fresh tomatoes.

The three packaging options considered are:

- "Loose" or minimally-packaged tomatoes transported in a corrugated container box with a General Purpose Polystyrene (GPPS) liner. Four tomatoes (2lbs) are purchased at a time by the consumer in a plastic (PE) produce bag;
- Four tomatoes (2 lbs) packaged in an EPS tray, wrapped in a PE film, and transported in bulk in corrugated cardboard boxes; and
- Four (2 lbs) tomatoes packaged in a PET clamshell container and transported in bulk in a corrugated cardboard box.

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[25] The relatively few studies on whole fruit and vegetable packaging, especially those that consider losses, led to the decision to include this study in the meta-analysis, even though it does not fully meet the selection criteria (it is more than 10 years old and was not peer reviewed).

Table B17 summarizes the main parameters of the study and provides an overview of the results. The functional unit chosen for the evaluation of packaging impacts was 100 lbs of tomatoes delivered to supermarket. For the analysis of the effect of packaging on the tomato life cycle impacts, a functional unit of 100 lbs of tomatoes delivered to consumer for consumption was chosen, to allow for the inclusion of tomato losses at retail.

The system boundary includes the growing and packaging of tomatoes, transport to warehouse and distribution to retail, storage and retail, and packaging disposal and recycling. Transportation to the end user is excluded, as is consumption of the tomatoes (including disposal of any uneaten tomatoes). Tomato losses at retail and their subsequent landfill disposal are included in a sensitivity analysis.

Summary of results and conclusions

Tomatoes sold loose have the same or lower environmental impacts than tomatoes sold in a PS tray and wrap. Tomatoes sold in a PET clamshell have the highest impacts, although the differences between the three options are slight.

Findings of the study include:

- Packaging fresh tomatoes in PET clamshells has the greatest impact across the four environmental impact categories considered in the study (global warming, acidification, respiratory effects, and smog).
- The differences between the three packaging options are relatively slight; the environmental impacts from fresh tomatoes in PS trays are 5 to 10% lower than tomatoes packed in PET clamshells, whilst loose tomatoes transported in corrugated containers have impacts 8 to 15 % lower than tomatoes in PET clamshells.
- The ranking of the three packaging options is consistent across the four environmental impact categories because all four impact categories are strongly influenced by the combustion of fuels.
- The PET clamshell scenario has the highest environmental impacts primarily because it requires a greater amount of plastic material and because PET manufacturing is more energy intensive than PE and PS.
- The contribution to impacts from packaging is surprisingly high across the four impact categories, given the relatively small amount of packaging material used, with packaging contributing 21%, 14% and 12% to GWP for the PET clamshells, PS trays and loose packaging options, respectively. Transportation of the tomatoes contributes over 50% of the life cycle impacts, whilst the impacts associated with tomato growing are slightly larger than packaging.

In a sensitivity analysis that assumed packaging reduces tomato spoilage at retail by 2%, the PS tray became the preferred option by a slim margin (with a GWP just under 2% lower than the loose option). However, the PET clamshell remained the least preferred, albeit by a small margin (with a GWP 5% higher than the loose option). The study notes that these results are based on very limited data on spoilage rates in supermarkets and that further investigated is warranted.

The study also notes other considerations that are relevant to packaging decision-making, including product marketing and merchandising, hygienic or visual appeal of the product, the influence of packaging and shelf life extension on consumers' trips to the store, and in inducing consumers to use additional packaging.

Table B17: Summary table: Stevenson *et al.* (2010)

		Products considered in study		
		PET clamshell	PS tray and wrap	Loose
Study scope	**Materials**	PET container, corrugated cardboard box	EPS tray and PE film, corrugated cardboard box	Corrugated cardboard box with GPPS liner; PE produce bag
	Functional unit (FU)	100 lbs (45.4 kg) of tomatoes delivered to the supermarket		
	Number per FU	50	50	50
	Weight per FU	898 g PET; 2.2 kg cardboard	150 g PS; 200 g PE; 2.2 kg cardboard	63.5 g PS; 150 g PE; 2.2kg cardboard
	Geographic region	USA		
	Life cycle stages	Growing and packaging of tomatoes, transport to warehouse and distribution to retail, storage and retail, and packaging disposal and recycling.		
	End of life assumptions	20% incinerated with energy recovery and 80% landfilled.	PS tray and GPPS box liner: 6.9% recycled, 18.6% incinerated with energy recovery and 74.5% landfilled. PE (wrap and produce bag): 14% recycled, 17.2% incinerated with energy recovery and 68.8% landfilled.	
		Corrugated box: 95% recycled, 1% incinerated with energy recovery and 4% landfilled.		
Indicators	Global warming	🟥	🟩	🟩
	Acidification	🟥	🟩	🟩
	Respiratory effects	🟥	🟩	🟩
	Smog formation	🟥	🟩	🟩
	Water consumption	🟥	🟩	🟩
Method	TRACI 3.01			
Data and software	Primary data (tomato growing), US LCI databases (PET and LDPE) and ecoinvent 2.0 database; SimaPro software			
Reviewed	No, but independent research with expert consultation			

Packaging Waste Prevention in the Distribution of Fruit and Vegetables: An Assessment Based on the Life Cycle Perspective: Tua *et al.* (2017)

This LCA was carried out to determine the environmental effectiveness of supplying locally grown fruit and vegetables in Italy direct to customers inside a returnable crate (a so-called "box scheme") compared to the traditional large-scale retail of fruit and vegetables.

Apples and carrots were chosen for the assessment. The box-scheme was compared to the following packaging options most prevalent at Italian supermarkets:

- LDPE polybag
- Tray and PVC stretch film (Carrots: PP tray; Apples: PS tray)
- Loose with HDPE purchasing bag

The system boundary of the **traditional (large-scale) distribution and retail of fresh produce** includes the packaging life cycle, i.e. the production and end-of-life treatment, and, for reusable crates, the cleaning and return to the packing plant after every use; the product packing operation; and the transport stages of the product (from the packing plant to the point of sale, as well as the car trip for the purchase).

The system boundary of the **box scheme** includes the life cycle of the packaging for transporting produce from the farm to the distribution hub, and the life cycle of the weekly crate; the preparation and cleaning of the weekly crates; and the transport stages of the product (from the farmer to the distribution hub, the delivery of the weekly crate (drop-off point or home delivery), including the return trip with empty crates, and the crate collection (drop-off delivery only).

The chosen functional unit for the study is the distribution of 1 kg of product (i.e. carrots or apples). Primary packaging is assumed to be manufactured from virgin raw materials, except for the cartonboard boxes which are produced from recycled fibres. The waste management system modelled is that of Northern Italy, using data on collection, sorting and recycling specific to this region for primary packaging and ecoinvent for transport packaging. Plastics recycling was modelled with avoided production; plastic lumber made from recycled plastic bags and PP trays were assumed to replace wooden planks. PS trays and stretch film were assumed to be incinerated in a waste-to-energy plant, with electricity (Italian grid mix) and thermal energy from domestic gas-fired boilers the avoided products. Cardboard boxes and PP crates were modelled with open-loop recycling, i.e. recycled material goes back into the manufacture of cardboard boxes and crates.

APPENDIX B

The main parameters of the study and an overview of the results are given in Table B18 and Table B19 for carrots and apples, respectively.

Summary of results and conclusions

For both carrots and apples, customers purchasing **loose products at large retail stores had the lowest impacts**. The box scheme with home delivery had similar impacts to the other traditional packaging types, whilst the box scheme with drop-off point delivery was the least environmentally preferred. The poor performance of the box scheme is largely a result of single-use crates/boxes used in the transport of produce from farm to distribution hub. If this were changed to reusable plastic crates (as in the traditional loose distribution network) then the box scheme with home delivery would become the best option for carrots and equal to the loose purchase option for apples.

Findings for carrots include:

- The least packaging waste and lowest environmental impacts are when carrots are sold loose and the customer completely fills their produce bag (1.5 kg).
- Carrots sold in a tray generated the highest packaging waste.
- The box scheme with home delivery generally has lower impacts than the 1-kg-tray and loose-carrots scenarios, as a result of the avoided primary packaging (in the case of the tray) and the avoided trips to the supermarket. However, the loose-carrots (1 kg) still comes out as environmentally preferred over the box scheme because of inefficiencies in the box scheme delivery system, specifically in the transport of carrots from the farm to the distribution hub. Improvements to the box scheme (shortening the distance from farm to distribution hub from 700 km to 100 km, and changing to reusable plastic crates rather than single-use wooden crates) was able to move the box scheme to becoming the environmentally preferred option.

Findings for apples include:

- The box scheme with home delivery is generally better than the 4-apples-tray scenario, while it is worse, or at most comparable, with the other traditional scenarios. In particular, the box scheme has significantly higher impacts than loose apples in freshwater eutrophication, freshwater ecotoxicity, and human toxicity (non-cancer effects).
- The higher impacts of the box scheme are mainly a result of single-use cardboard boxes used in the transport of apples from farm to distribution hub. If reusable crates are used instead, the box scheme becomes environmentally preferred to all options, other than the 2-kg loose apples (completely filled bag).
- The 4-apples-tray scenario has the highest impacts in 13 out of 14 impact categories.

Table B18: Summary table: Tua *et al*. (2017)–Carrots

		Products considered in study				
		1 kg polybag	1 kg tray	Loose carrots – completely filled bag (1.5 kg)	Loose carrots – partially filled bag (0.4 kg)	Box-scheme (home delivery)[26]
Study scope	**Materials**	LDPE bag; PP reusable crate	PP tray and PVC stretch film; PP reusable crate	HDPE bag for purchase; PP reusable crate, LDPE carrier bag	HDPE bag for purchase; PP reusable crate, LDPE carrier bag	PP weekly crate; Wooden crate, LDPE carrier bag
	Functional unit (FU)	The distribution of 1kg of carrots				
	Number per FU (primary packaging)	1	1	0.67	2.5	0.004
	Weight [grams] (primary packaging)	9.8 g	Tray: 5.4 g Film: 3.6 g	2.8 g	2.8 g	1.13 kg
	Geographic region	Italy (Lombardy)				
	Life cycle stages	For packaging, raw materials, production and end-of-life treatment, and, for reusable crates, cleaning and return to the packing plant after every use; packing operation; and transport (farm to point-of-consumption)				Packaging life cycle; preparation and cleaning of the weekly crates; and transport
	Use phase assumptions	PP reusable crates and weekly crate filled 50 times, return transport and cleaning of crates included (water, cleanser, disinfectant and energy)				
	End of life assumptions	End-of-life modelling represents the situation in Northern Italy (PE bags and PP trays recycled as mixed polyolefins; PS trays and film incinerated; carboard and PP crate recycled into same product system).				
Indicators	**Climate change**	🟨	🟥	🟩	🟥	🟨
	Ozone depletion	🟨	🟥	🟩	🟥	🟨
	Photochemical ozone formation	🟨	🟨	🟩	🟥	🟨
	Acidification	🟨	🟥	🟩	🟥	🟨
	Terrestrial eutrophication	🟨	🟨	🟩	🟥	🟥
	Freshwater eutrophication	🟨	🟥	🟩	🟥	🟨
	Marine eutrophication	🟨	🟥	🟩	🟥	🟥
	Freshwater ecotoxicity	🟨	🟥	🟩	🟥	🟨
	Human toxicity (cancer effects)	🟨	🟥	🟩	🟥	🟨
	Human toxicity (noncancer effects)	🟨	🟥	🟩	🟨	🟥
	Particulate matter	🟨	🟥	🟩	🟨	🟥
	Water resource depletion	🟨	🟥	🟩	🟨	🟨
	Mineral and fossil resource depletion	🟨	🟥	🟩	🟥	🟨
	Cumulative energy demand	🟨	🟥	🟩	🟥	🟨

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[26] As delivery systems are not the focus of the meta-analysis, only the scenario for home delivery is shown in the table. The study evaluates three different delivery scenarios (home delivery, drop off delivery where customer makes a dedicated car trip to fetch the box, and drop off delivery where customer purchases additional items whilst fetching the box). Home delivery is environmentally preferred to both the drop off delivery scenarios.

Table B18: Continued – Summary table: Tua *et al*. (2017)–Carrots

	Products considered in study				
	1 kg polybag	1 kg tray	Loose carrots – completely filled bag (1.5 kg)	Loose carrots – partially filled bag (0.4 kg)	Box-scheme (home delivery)[26]
Method	Characterization methods recommended by the Joint Research Centre of the European Commission, other than for mineral and fossil resource depletion which is on the basis of the "ultimate reserves" of resources. Cumulative energy demand was also calculated.				
Data and software	Ecoinvent database and SimaPro software				
Reviewed	Peer-reviewed journal article				

Table B19: Summary table: Tua *et al*. (2017)–Apples

		Products considered in study				
		2 kg polybag	4 apple tray	Loose apples – completely filled bag (2 kg)	Loose apples – partially filled bag (0.9 kg)	Box-scheme (home delivery)[27]
Study scope	**Materials**	LDPE bag; Cardboard box	PS tray and PVC stretch film; Cardboard box	HDPE bag for purchase; PP reusable crate	HDPE bag for purchase; PP reusable crate	PP weekly crate; Cardboard box, PP fruit nest tray
	Functional unit (FU)	The distribution of 1kg of apples				
	Number per FU (primary packaging)	0.5	1.1	0.5	1.1	0.004
	Weight [grams] (primary packaging)	9.8 g	Tray: 5.4 g Film: 3.6 g	2.8 g	2.8 g	1.13 kg
	Geographic region	Italy (Lombardy)				
	Life cycle stages	For packaging, raw materials, production and end-of-life treatment, and, for reusable crates, cleaning and return to the packing plant after every use; packing operation; and transport (farm to point-of-consumption)				Packaging life cycle; preparation and cleaning of the weekly crates; and transport
	Use phase assumptions	PP reusable crates and weekly crate filled 50 times, return transport and cleaning of crates included (water, cleanser, disinfectant and energy)				
	End of life assumptions	End-of-life modelling represents the situation in Northern Italy (PE bags and PP trays recycled as mixed polyolefins; PS trays and film incinerated; carboard and PP crate recycled into same product system).				

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[27] As delivery systems are not the focus of the meta-analysis, only the scenario for home delivery is shown in the table. The study evaluates three different delivery scenarios (home delivery, drop off delivery where customer makes a dedicated car trip to fetch the box, and drop off delivery where customer purchases additional items whilst fetching the box). Home delivery is environmentally preferred to both the drop off delivery scenarios.

Table B19: Continued – Summary table: Tua *et al*. (2017)–Apples

		Products considered in study				
		2 kg polybag	4 apple tray	Loose apples – completely filled bag (2 kg)	Loose apples – partially filled bag (0.9 kg)	Box-scheme (home delivery)[27]
Indicators	**Climate change**	🟨	🟥	🟩	🟨	🟨
	Ozone depletion	🟩	🟥	🟩	🟥	🟥
	Photochemical ozone formation	🟩	🟥	🟩	🟨	🟨
	Acidification	🟨	🟥	🟩	🟨	🟨
	Terrestrial eutrophication	🟨	🟥	🟩	🟨	🟨
	Freshwater eutrophication	🟨	🟨	🟩	🟨	🟥
	Marine eutrophication	🟨	🟥	🟩	🟨	🟨
	Freshwater ecotoxicity	🟨	🟥	🟩	🟨	🟨
	Human toxicity (cancer effects)	🟨	🟥	🟩	🟨	🟨
	Human toxicity (noncancer effects)	🟨	🟥	🟩	🟨	🟥
	Particulate matter	🟨	🟥	🟩	🟨	🟥
	Water resource depletion	🟨	🟥	🟩	🟨	🟨
	Mineral and fossil resource depletion	🟨	🟥	🟩	🟨	🟨
	Cumulative energy demand	🟨	🟥	🟩	🟨	🟨
Method	Characterization methods recommended by the Joint Research Centre of the European Commission, other than for mineral and fossil resource depletion which is on the basis of the "ultimate reserves" of resources. Cumulative energy demand was also calculated.					
Data and software	Ecoinvent database and SimaPro software					
Reviewed	Peer-reviewed journal article					

B.2.3 Transit packaging for fresh produce (fruit and vegetables, bread)

When Plastic Packaging Should Be Preferred: Life Cycle Analysis of Packages for Fruit and Vegetable Distribution in the Spanish Peninsular Market: Abejón *et al*. (2020)

The aim of this LCA was to obtain objective information on the environmental impact associated with the distribution of fruits and vegetables in the domestic Spanish (peninsular) market. Reusable collapsible plastic crates and single-use cardboard boxes are compared in two scenarios. In the conservative scenario (which is taken as baseline), the useful life of the plastic crate is 10 years and 10 rotations per year are considered; while the technical scenario extends the use to 15 rotations per year, keeping the lifetime unchanged (10 years).

The full life cycle of both distribution systems is considered, including extraction of raw materials, manufacturing the packages, the distribution and use stages, and end-of-life processing. System expansion is applied in modelling recycling and incineration with energy recovery at end-of-life (i.e. the environmental impacts associated with obtaining materials and energy from alternative production sources are subtracted from the packaging system).

The main parameters of the study and an overview of the results are given in Table B20.

Summary of results and conclusions

The **reusable plastic crates were found to have significantly lower environmental impacts and energy consumption than the single-use cardboard boxes.** This was true across all impact categories and for both scenarios (technical and conservative).

For the reusable plastic crates:

- Their lower impacts relative to single-use boxes are a result of their lower consumption of materials. Energy and freshwater consumption are also lower for the reusable plastic crates when compared to the single-use cardboard boxes.
- The service life cycle stage (use phase) is the largest contributor to the impact categories and energy consumption, followed by production.
- The results of the conservative and technical scenarios are very similar, with the technical scenario having marginally lower impacts.

For the single-use cardboard boxes:

- The production stage is the largest contributor to all the impacts (except GWP). For GWP, the impacts are spread between production (38%) and end-of-life (61%). Box production is also the largest contributor to energy consumption (94%) and freshwater consumption.

A very rigorous set of sensitivity analyses, data quality assessment, completeness and consistency checks allow a **high degree of confidence in the preference for the reusable plastic crates:**

- For all the parameters modified in the sensitivity analysis, the clear preference for the reusable plastic crates is maintained. In most cases the plastic crates had a least 25% lower impact than the cardboard boxes.
- The most important parameter/assumption affecting the performance of the reusable plastic crates is the percentage of plastic crates recycled at the end of their useful life. When the recycling percentage is reduced from 100% to 50% the GWP and ozone depletion potential increases by 24% and 11% respectively.
- Only at high (hypothetical) levels of recycled content in the boxes, did they have lower impacts than the plastic crates in some impacts. However, the altered composition and reduction in the quality of the cardboard has not been tested as feasible.

Table B20: Summary table: Abejón *et al*. (2020)

		Products considered in study	
		Reusable plastic crate	Single-use cardboard box
Study scope	**Materials**	Plastic: HDPE (57%) and PP (43%)	Cardboard: semi-chemical pulp (63%) and Kraftliner (37%)
	Functional unit (FU)	Conservative scenario: Distribution of 6,666,700 packages full of fruits and vegetables, with a transported weight of 15 kg (1,000 metric tons of fruits and vegetables); Technical scenario: Distribution of 10,000,050 packages full of fruits and vegetables, with a transported weight of 15 kg	
	Number per FU	Conservative scenario: 100,668 (66,667 initial production and 34,001 additional production); Technical scenario: 117,668 (66,667 initial production and 51,001 additional production	Conservative scenario: 6,666,700 Technical scenario: 10,000,050
	Weight [grams]	Plastic crate: 1,790 g	Cardboard box: 0.807 g
	Geographic region	Spain (Spanish peninsular market)	
	Life cycle stages	Full life cycles of both distribution systems, covering extraction of raw materials for manufacturing the packages, the distribution and use stages, and the end-of-life processing as waste	
	Use phase assumptions	10 year lifetime with breakage rate of 0.51% per use. Consumption of water (0.5 l per crate) and caustic detergent (0.2% concentration) considered in use phase washing	N/A
	End of life assumptions	100% recycled	80% recycled (used in manufacture of new boxes) and 20% incinerated with energy recovery
Indicators	Global warming potential (GWP)	🟩	🟥
	Ozone depletion	🟩	🟥
	Human toxicity	🟩	🟥
	Acidification potential	🟩	🟥
	Eutrophication potential	🟩	🟥
	Ozone depletion potential	🟩	🟥
	Photochemical oxidant creation potential (POCP)	🟩	🟥
	Water consumption	🟩	🟥
	Energy consumption	🟩	🟥
Method	CML, other than POCP (using IMPACT 2002+). Total freshwater use also considered.		
Data and software	GaBi 7; Data from industry, GaBi database 2016 used for the manufacturing stages of plastic crates and cardboard boxes.		
Reviewed	Peer-reviewed journal article		

An Extended Life Cycle Analysis of Packaging Systems for Fruit and Vegetable Transport in Europe: Albrecht *et al*. (2013)

In this LCA, the most common European fruit and vegetable transport packaging systems, namely single-use wood crates, single-use cardboard boxes and reusable plastic crates are compared considering their environmental, economic and social impacts. Economic aspects are considered by performing Life Cycle Costing (LCC) and social impacts with a Life Cycle Working Environment (LCWE) assessment.

The main parameters of the study and an overview of the results are given in Table B21.

Summary of results and conclusions

Plastic crates and wooden boxes have lower impacts than cardboard boxes for fruit and vegetable transport in Europe, across all impact indicators included in the study. The high impacts of the boxes arise mainly as a result of the high-quality cardboard required for the transport of fruit and vegetables. The plastic crates and wooden boxes have similar impacts with respect to their global warming and acidification potentials, with the **plastic crates having the lowest impacts overall**.

Findings include:

- The reusable plastic crates have the lowest impacts in four impact categories, and similar results to the wood crates for GWP and ADP. The **use phase is the largest contributor to the impacts of the reusable crates**, particularly long distance transport as well as washing. The production of plastic granulate is also an important contributor to environmental impacts.
- The single-use wood crate has the lowest GWP and ADP, along with the reusable plastic crate. Production is the most significant contributor to the impacts, most notably production of the crates, distribution, and forestry and timber production. Incineration is the most significant contributor to the wood crates' GWP.
- The single-use cardboard box has the worst performance across all impact categories. As with the wood crates, production is the largest contributor to the impacts. This is mainly a result of pulp and paper production, cardboard production and, to a lesser extent, forestry and wood production. Incineration is also a significant contributor to GWP.

Table B21: Summary table: Albrecht *et al*. (2013)

		Products considered in study		
		Single-use wood crate	Single-use cardboard box	Reusable plastic crate
Study scope	**Materials**	Wood	Corrugated cardboard	Plastic (PP and PE)
	Functional unit (FU)	The distribution of 15 kg of fruits/vegetables in 3,333,350 filled boxes/crates		
	Number per FU	3,333,350	3,333,350	66,667 initial production and 15,667 replacement crates
	Weight per box	0.9 kg	0.823 kg	2 kg
	Geographic region	Europe (Spain, Italy, France, the Netherlands, Germany and Great Britain)		
	Life cycle stages	Full life cycles of each packaging system, covering raw materials production, product manufacture, distribution, use, and end of life (energy recovery and material recycling).		
	Use phase assumptions	N/A	N/A	5 fillings per year over a lifetime of 10 years; average breakage rate of 0.47%
	End of life assumptions	Incineration with energy recovery (baseline assumption); recycling into particleboard (parameter analysis)	17.6 % recycled back into pulp and paper production with balance incinerated with energy recovery (baseline)	Recycled (open loop) with the value of the secondary granulate set to 70 % of the virgin material (baseline)

Table B20: Continued – Summary table: Albrecht *et al.* (2013)

		Products considered in study		
		Single-use wood crate	Single-use cardboard box	Reusable plastic crate
Indicators	Primary Energy Demand	🟨	🟥	🟩
	Global Warming Potential	🟩	🟥	🟩
	Acidification Potential (AP)	🟨	🟥	🟩
	Eutrophication Potential (EP)	🟨	🟥	🟩
	Photochemical Ozone Creation Potential (POCP)	🟨	🟥	🟩
	Abiotic Resource Depletion Potential (ADP)	🟩	🟥	🟩
Method	CML			
Data and software	GaBi. Background data (such as energy, transport, and auxiliary materials) taken from GaBi 4.			
Reviewed	Critical review by an independent expert panel; peer-reviewed journal article			

Comparative Lifecycle Assessment of Mango Packaging Made from a Polyethylene/Natural Fiber-Composite and from Cardboard Material: Bernstad Saraiva *et al.* (2016)

The aim of this study was to investigate the environmental impacts from production, use and end-of-life treatment of three types of materials to be used in the transport of mango fruits in Brazil. Specifically, the study compares a composite packaging designed specifically for reusability and for the reduction of mango losses in the supply chain with that of traditional cardboard boxes. The mango packaging developed consists of reusable frame and a high impact polystyrene (HIPS) recyclable tray. Three versions of the packaging were evaluated:

- Reusable frame made from 100% HDPE
- Reusable frame made from HDPE reinforced with 10% natural sponge fibre residue
- Reusable frame made from HDPE reinforced with 30% natural sponge fibre residue

A further objective of the study was to determine the number of reuses of the composite packaging required for it to become environmentally preferred to the cardboard packaging. For this, two scenarios were developed:

- Transport and end-consumption in Brazil
- Transport to end-consumers in Europe.

The main parameters of the study and an overview of the results are given in Table B22. The functional unit is chosen as the transportation of ten mangos per packaging from the area of production to the end-consumer. The study considered the following stages in the life cycle of the packaging; raw materials acquisition, transformation and assembly, distribution to fruit producers, distribution to end-consumers and end-of-life treatment. All packaging is produced in Brazil. The natural fibres used in the composite packaging are sponge-gourd residue, obtained directly from a local bath sponge factory. The natural fibres used in the packaging were credited with the avoided emissions of disposal, and only their subsequent processing for use in the packaging (milling) was included in the LCA model. Similarly, for the recycled HDPE used in the composite frame, only the emissions associated with the recycling of the HDPE were included in the LCA model. The HIPS tray and cardboard box are assumed to be produced from virgin materials.

The end-of-life for the two scenarios (end-consumption in Brazil or Europe) are modelled for plastic and cardboard waste management in Brazil and Europe (see Table B22). System expansion/avoided production is applied in the modelling, with recycled HIPS assumed to substitute virgin polymer to 95%.

APPENDIX B

Summary of results and conclusions

If the packaging is used only once, the cardboard box scores the lowest across all impact category indicators other than ozone depletion potential. The 100% recycled HDPE frame is the least preferred, with environmental preference for the composite frame increasing in some impact categories with increasing percentage of natural fibres.

The composite frame with 30% fibres has to be reused four times on the local market for it to break even with the cardboard box (in terms of its climate change impact), and reused 35 times if transported to Europe.

Additional findings include:

- The better environmental performance of the frame with natural fibres relative to the 100% HDPE frame is slight and only in some impact categories (climate change, human toxicity carcinogens, photochemical oxidant formation and acidification). This is because of the additional energy required in producing the composite (processing the HDPE and sponge-gourd discards) and the resultant higher weight of the composite frame.
- The greatest contribution to climate change impact of the composite packaging is the production of the HIPS tray; whilst the highest contributor to the cardboard packaging is the production and transformation of fibres into cardboard.
- When used on the local Brazilian market, the composite frame with 30% fibres required fewer uses to break even with the cardboard box (in terms of climate change impact) than the composite frame with 10% fibres (at 4 uses and 9 uses, respectively). However, the opposite was found for mangos exported to Europe, with the composite frame with 10% fibres requiring 29 uses to break even compared with 35 uses for the composite frame with 30% fibres.
- The higher number of reuses to break even when end-consumption is in Europe is largely due to differences in end-of-life treatment in Brazil and Europe, with incineration with energy recovery significantly improving the relative environmental performance of the cardboard boxes.

Table B22: Summary table: Bernstad Saraiva *et al*. (2016)

		Products considered in study			
		Composite packaging, 0% natural fibres	Composite packaging, 10% natural fibres	Composite packaging, 30% natural fibres	Cardboard box
Study scope	**Materials**	Recycled HDPE frame; HIPS tray	Recycled HDPE reinforced with 10% natural fibres; HIPS tray	Recycled HDPE reinforced with 30% natural fibres; HIPS tray	Cardboard
	Functional unit (FU)	Transportation of ten mangos per packaging from the area of production to the end-consumer			
	Number per FU	1	1	1	1
	Weight [grams]	Frame: 573.3 g HDPE; Tray: 68.7 g HIPS	Frame: 550.8 g HDPE, 61.2 g fibre; Tray: 68.7 g HIPS	Frame: 493.3 g HDPE, 211.4 g fibre; Tray: 68.7 g HIPS	358 g
	Geographic region	Production of raw materials and packaging in Brazil, waste management either in Brazil or Europe			
	Life cycle stages	Full life cycle of the packaging (raw materials acquisition, transformation and assembly, distribution to fruit producers, distribution to end-consumers and end-of-life treatment). Excludes contents (mangos).			
	Use phase assumptions	Washing impacts and breakage rate based on those of plastic crates (Albrecht *et al.* 2013)			n/a
	End of life assumptions	Brazil: HIPS–21% recycled, 79% landfilled; Frame–landfilled Europe: HIPS – 35% recycled, 35% energy recovery, 30% landfilled; Frame – incinerated with energy recovery			Brazil: landfilled Europe: incinerated with energy recovery

Table B21: Continued – Summary table: Bernstad Saraiva *et al.* (2016)

Indicators	Climate change	🟥	🟨	🟨	🟩
	Ozone depletion potential	🟥	🟥	🟨	🟥
	Particulate matter	🟥	🟨	🟨	🟩
	Photochemical oxidation potential	🟥	🟨	🟨	🟩
	Acidification	🟥	🟨	🟨	🟩
	Eutrophication marine water	🟥	🟥	🟥	🟩
	Eutrophication freshwater	🟥	🟥	🟨	🟩
	Human toxicity carcinogenic	🟥	🟥	🟥	🟩
	Human toxicity non-carcinogenic	🟥	🟥	🟨	🟩
	Ecotoxicity	🟥	🟨	🟨	🟩
Method	LCIA methods and impact categories recommended in the ILCD Handbook (Recommendations for Life Cycle Impact Assessment in the European context).				
Data and software	Mango box production largely based on primary data; cardboard box primarily secondary data. Background system processes were modelled as much as possible using data representative of the Brazilian context. Modelled in SimaPro v8.04.				
Reviewed	Peer-reviewed journal				

Sustainable Packaging: An Evaluation of Crates for Food through a Life Cycle Approach: *Del Borghi* et al. *(2021)*

This LCA compares the environmental impacts of food delivery in Europe across a range of materials from which food-contacting crates are made (plastic, corrugated board, solid wood, medium-density fibreboard and particleboard). Single-use and multi-use systems were considered. A secondary objective of the study was to identify the critical parameters influencing the environmental impacts of multi-use crates.

The main parameters of the study and an overview of the results are given in Table B23.

Summary of results and conclusions

Reusable plastic crates are strongly preferred across all environmental indicators considered. Considering single-use crates, solid wood crates had the best environmental performance and plastic crates the worst.

- The reusable plastic crates have the lowest impacts across all impact categories other than cumulative energy demand. The low impacts are a consequence of reuse avoiding production impacts. The transport phase is a significant contributor to GWP (41%), highlighting the importance of including transport in the system boundaries.
- The solid wood crates have the second lowest impacts, with lower impacts than the MDF and particle board crates. This is due to solid wood being a less processed material than MDF and particle board.
- The single-use plastic crates have the highest impacts across most impact categories, mainly attributed to the high impacts of HDPE and PE production.
- The impacts of the corrugated board crate are strongly related to paper production.

Two sensitivity analyses where performed: varying the transport network option (only performed on the reusable plastic crates and solid wood crates) and varying the end-of-life scenario (only the plastic crates).

- Changing the distances by +-5%, +-15% and +-25% has a more significant effect on the GWP of the reusable plastic crates than the solid wood crates (2% vs 0.67% increase in GWP for each 5% increase in distance respectively).
- Increasing the percentage of plastic crate recycling from 0% to 100% results in a 14.7% decrease in GWP.

APPENDIX B

Table B23: Summary table: Del Borghi *et al*. (2021)

		Products considered in study					
		Reusable plastic crates	Single-use plastic crates	Corrugated board crates	Wood crates		
					Solid	MDF	Particle board
Study scope	**Materials**	HDPE (58.4%) and PP (41.6%)		58.6% kraft liner paper and 41.4% semi-chemical fluting	Spruce (13%), poplar (70%) and pine (17%)	Wood chips and residue	
	Functional unit (FU)	One standard crate, i.e. a crate with external dimensions of 400 x 600 x 240 mm and an inner volume of 50 litres.					
	Number per FU	1	1/50	1	1		
	Weight per box	2 kg		1.086 kg	0.9 kg	1 kg	1.4 kg
	Geographic region	Europe					
	Life cycle stages	Full life cycles of each packaging system, covering raw materials acquisition, crate manufacturing, transport (including the reuse, where applicable), and final disposal					
	Use phase assumptions	50 uses over 5-year lifetime. Use phase includes transports, cleaning/ sanitization, and waste water treatment	N/A	N/A			
	End of life assumptions	Incineration (7%) and recycling (93%)		Incineration (22%) and recycling (78%)	In-house combustion (24%), recycling (41%), composting (9%), waste-to-energy (3%), landfill (23%)		
	Global Warming Potential	🟩	🟥	🟨	🟨	🟨	🟨
	Acidification Potential (AP)	🟩	🟥	🟨	🟩	🟩	🟩
	Eutrophication Potential (EP)	🟩	🟩	🟩	🟩	🟩	🟩
	Cumulative Energy Demand	🟥	🟨	🟨	🟨	🟩	🟨
	Human toxicity	🟩	🟨	🟥	🟨	🟨	🟨
	Marine toxicity	🟩	🟥	🟨	🟨	🟨	🟨
	Terrestrial toxicity	🟩	🟨	🟥	🟨	🟨	🟨
	Freshwater toxicity	🟩	🟥	🟨	🟨	🟨	🟨
Method	CML 2001 and cumulative energy demand						
Data and software	Sector studies, literature and ecoinvent.						
Reviewed	Peer-reviewed journal article						

Reusable Plastic Crate or Recyclable Cardboard Box? A Comparison of Two Delivery Systems: Koskela *et al*. (2014)

The aim of this study was to compare the life cycle environmental impacts of a real bread delivery system using either reusable plastic crates or recyclable corrugated cardboard boxes for product transportation. The delivered product was toast bread, a light-weight packaged daily foodstuff produced in Estonia and delivered across Finland.

The plastic crate and cardboard box systems have the same boundaries with many identical components, such as delivery routes from bakery to retailers and primary bread packaging (plastic bag). The systems differed in the manufacturing of crates/boxes, their use, transportation impacts in delivery (crate collection and take-back) and waste management/ recycling of the crates/boxes. Transport is modelled in detail, assuming trucks are volume rather than weight limited. System expansion (avoided production) is applied in modelling waste recovery.

The function of the studied systems was to distribute bread from bakery to consumers. The functional unit of the product systems was 8 loaves of bread delivered in one crate/box. Plastic crates were manufactured in Finland and transported to Tallinn, Estonia, where the bread was baked. In the cardboard box system the sheets of corrugated board were manufactured and cut in Latvia and transported to Tallinn. At the bakery, the boxes were assembled from the blanks in the box forming machine. Packed bread was then transported in crates or boxes from Tallinn (via Helsinki) to the main distribution centre in Eastern Finland.

The main parameters of the study and an overview of the results are given in Table B24.

Summary of results and conclusions

The **recyclable cardboard box system was found to have lower impacts than the reusable HPDE plastic crate system across all impact categories considered.** Transportation was found to play a very important role in the environmental impacts, demonstrating the importance of the weight of products being transported and transport distances in determining environmental preference between cardboard boxes and reusable plastic crates.

Findings include:

- **Transportation is the most significant contributor to all studied environmental impacts.** The greatest differences in the impacts of transportation between the crates and boxes are caused by the different weights of the crates/boxes and by the circulations of plastic crates (greater distances transported overall).
- The environmental impacts of manufacturing one HDPE plastic crate are higher than those of one cardboard box, but are lower over the life cycle since the fact that crates are reused hundreds of times decreases their impacts substantially.
- The contribution of crate washing to the total impacts is very low.
- Recycling the cardboard boxes into coreboard generates significant benefits, most notably in the climate change impact category. Without the recycling credit, the climate change impact of the cardboard box system would be 12% higher, but still lower than the climate impact of the plastic crate system. The benefits of the recovery of plastic crates are insignificant.
- Normalized results indicated that the lowest contribution to European impacts was to climate change and the highest to fossil depletion.

APPENDIX B

Table B24: Summary table: Koskela *et al*. (2014)

		Products considered in study	
		Reusable plastic crate	Single-use cardboard box
Study scope	**Materials**	HDPE	Corrugated cardboard
	Functional unit (FU)	8 loaves of bread delivered in one crate/box.	
	Number per FU	1/700 (average lifetime of 13.75 years, 61.54 circulations per year and 4.87 days for one circulation)	1
	Weight	1.45 kg	0.19 kg
	Geographic region	Finland, with crates packed (bread baked) in Estonia.	
	Life cycle stages	Full life cycles of the delivery systems, covering the manufacturing of the crates/boxes, their use, the delivery routes from bakery to retailers and waste management/recycling of the crates/boxes.	
	Use phase assumptions	Empty crates transported back to the main distribution centre for washing and then back to the bakery in Estonia.	N/A
	End of life assumptions	20% recycled (system expansion avoiding impregnated wood), 80% energy recovery	100% recycled (system expansion avoiding coreboard produced with virgin material)
Indicators	Climate change	🟥	🟩
	Terrestrial Acidification	🟥	🟩
	Photochemical oxidant formation	🟥	🟩
	Particulate matter formation	🟥	🟩
	Fossil depletion	🟥	🟩
	Freshwater eutrophication	🟩	🟩
Method	ReCiPe midpoint (Hierarchist)		
Data and software	Ecoinvent v. 2.2 database, Finnish Lipasto Database (transport emissions) and published studies (waste recovery).		
Reviewed	Critical review by an independent expert panel; peer-reviewed journal article		

A Comparative Life Cycle Assessment of Disposable and Reusable Packaging for the Distribution of Italian Fruit and Vegetables: Levi *et al*. (2011)

The aim of this study was to suggest design solutions to make the distribution of 12 types of fruit and vegetables in Italy and Europe more sustainable. One-way corrugated boxes and reusable plastic containers of various sizes were considered.

The main parameters of the study and an overview of the results are given in Table B25.

Summary of results and conclusions

The **reusable plastic crate system is environmentally preferred when transport distances are less than 1,200 km.** At distances higher than this, the corrugated cardboard box has the lower environmental impacts (baseline case study assumed a transport distance of 2,000 km). The number of uses is important for the plastic crate system, but after 20 uses, increasing the uses further has little effect on impacts (asymptotic relationship). For the boxes, where the material production has a higher contribution to life cycle impacts than in the plastic crates, bigger boxes result in lower impacts.

Findings include:

- Cardboard boxes have the lowest impact for global warming potential, ozone layer depletion potential and photochemical oxidation. This is reversed (with reusable plastic crates having the lowest impacts) when transport distances are below 1,200 km.
- The reusable plastic container and cardboard boxes have almost equal impacts for eutrophication and non-renewable resources, whilst cardboard boxes have higher potential acidification impact.
- **Transport impacts contribute the most to the life cycle impacts**, with the effect of transport distances more pronounced on the reusable plastic crates. Production phase impacts are relatively more important for the cardboard boxes than the plastic crates.
- The study also investigated the impact of varying the box/crate size. For both containers, the largest size has the lowest impact as a result of decreasing the tare/net weight ratio.
- A sensitivity analysis considered the number of possible uses of the plastic crates, ranging from 1 to 400 (baseline results assume 200 uses). Increasing the number of uses substantially reduces the impact of the plastic containers when reuse numbers are low. However, the reduction in impact with each reuse drops significantly after 20 uses, and after 50 uses the decrease in environmental impact with each subsequent use is insignificant.
- The percentage of crates washed was varied between 0% and 100% (baseline results assume 25% of crates are washed) and found to have a negligible effect on impacts (washing percentage of 0% results in a reduction in impacts of less than 4% and a washing percentage of 100% results in an increase of less than 11%).

Table B25: Summary table: Levi *et al*. (2011)

		Products considered in study	
		Reusable plastic crate	Single-use cardboard box
Study scope	**Materials**	PP (virgin material)	Corrugated cardboard (60% kraft paper and 40% semichemical paper) (virgin materials)
	Functional unit (FU)	100 kg of fruits and vegetables available at large-scale retail outlets within Italy and in Europe	
	Weight	2.1 kg	0.7 kg
	Geographic region	Fruit and vegetables grown and harvested in Italy, and sold in Italy and Europe	
	Life cycle stages	Full life cycle, covering materials production, box/crate production, transports and end-of-life.	
	Use phase assumptions	200 uses (20 uses a year for 10 years); average of one container out of four is washed (both parameters varied in sensitivity analyses)	N/A
	End of life assumptions	95% recycled (system expansion avoiding virgin PP production) with balance ending up in municipal waste stream	96% recycled (system expansion avoiding testliner paper production) with balance ending up in municipal waste stream
Indicators	GWP	🟥	🟩
	Ozone depletion potential	🟥	🟩
	Photochemical oxidation	🟥	🟩
	Acidification	🟩	🟥
	Eutrophication	🟩	🟩
	Use of non-renewable resources	🟩	🟩
Method	Impact categories recommended by the Environmental Product Declaration (EPD) international system of certification and communication promoted by the Swedish Environmental Management Council (SEMC).		
Data and software	Data was provided by the Italian Group of Manufacturers of Corrugated Cardboard (GIFCO), literature and ecoinvent (v 2.0)		
Reviewed	Peer-reviewed journal article		

APPENDIX B

Life Cycle Assessment of Reusable Plastic Crates (RPCs): Tua *et al*. (2019)

The aim of this LCA was to assess the life cycle environmental performance of RPCs as a function of the number of deliveries, with a special focus on the reconditioning stage. The study also compares the reusable plastic crate system with an alternative plastic crate system in which the crates are 60% lighter but used only once.

Based on the collected primary data, four scenarios are analysed to consider possible differences in the crate reconditioning process, varying the percentage of crates washed and the type and amounts of chemicals used.

The main parameters of the study and an overview of the results are given in Table B26.

Summary of results and conclusions

The reuse/reconditioning stage starts to dominate the life cycle impacts of RPCs after about 20 uses (before that the production stage accounts for the main share of impacts). Within the reconditioning stage, transport of crates from users to the reconditioning plant account for the main share of impacts, followed by the electricity consumption of the reconditioning plant.

The **RPC system has lower environmental impacts than single-use plastic crates (across all environmental indicators) after just three uses.**

Findings include:

- The four scenarios showed the impacts of washing to be mostly influenced by the percentage of crates washed, with the type and quantity of washing chemicals less important in comparison.
- Most of the environmental burdens are associated with the transportation of the crates from the users to the reconditioning plant (especially for particulate matter, photochemical ozone formation, terrestrial and marine eutrophication, and resource depletion). The electricity consumption of the reconditioning plant is an important contributor to freshwater eutrophication and ecotoxicity.

Table B26: Summary table: Tua *et al*. (2019)

		Products considered in study	
		Collapsible reusable plastic crate	Lightweight single-use plastic crate
Study scope	**Materials**	PP (100% virgin for starting crates, closed loop recycling leading to 61% secondary PP in replacement crates)	PP
	Functional unit (FU)	1,200 kg (corresponding to 100 RPCs) of carrying capacity at each delivery	
	Number per FU	Varied from 1 to 125 reuses, i.e. 0.8 to 100 per FU. Results below are for 33 per FU or less (i.e. 3 rotations or more)	100
	Weight	1.49 kg	0.579 kg
	Geographic region	Northern Italy	
	Life cycle stages	Full life cycle, covering crate production, reconditioning process (including transportation from users to reconditioning, consumption of electricity, water, fuel and chemicals in washing process, wastewater treatment and incineration of solid residues removed from the crates), and end-of-life (recycling). Packing of the product and transportation of crates to retail are excluded.	
	Use phase assumptions	Two scenarios with different washing rates and breakages: 100% of crates washed and breakage rate of 0.55%; 55% of crates washed and breakage rate of 0.46% Two scenarios with different detergent and disinfectant formulations	N/A
	End of life assumptions	Closed-loop recycling with system expansion (avoided production), 93% recycling efficiency and substitution factor of 1:0.66 (by mass)	
Indicators	Ozone depletion	🟩	🟥
	Photochemical ozone formation	🟩	🟥
	Acidification	🟩	🟥
	Terrestrial eutrophication	🟩	🟥
	Freshwater eutrophication	🟩	🟥
	Marine eutrophication	🟩	🟥
	Freshwater ecotoxicity	🟩	🟥
	Human toxicity (cancer effects)	🟩	🟥
	Human toxicity (noncancer effects)	🟩	🟥
	Particulate matter	🟩	🟥
	Water resource depletion	🟩	🟥
	Mineral and fossil resource depletion	🟩	🟥
	Cumulative energy demand	🟩	🟥
	Ozone depletion	🟩	🟥
Method	ILCD (12 impact categories), CED and water resources depletion (net water consumption in m^3)		
Data and software	Primary data (crate pooling), literature (waste recovery) and ecoinvent. SimaPro software.		
Reviewed	Peer-reviewed journal article		

B.3 PANTRY: SHELF STABLE AND DRY GOODS

B.3.1 Shelf stable

Glass vs. Plastic: Life Cycle Assessment of Extra-Virgin Olive Oil Bottles across Global Supply Chains: Accorsi, Versari and Manzini (2015)

This study explores the environmental impacts of a global supply chain for extra-virgin olive oil (EVOO), with a focus on packaging decisions. The study is for olive oil produced in Greece and Spain, bottled in Italy and distributed worldwide. The aim was to determine the environmental impacts associated with the bottled EVOO life cycle, focusing on packaging decisions. Three different bottles were considered–glass, virgin PET and PET with recycled content (rPET)–each with two secondary packaging alternatives, as follows:

- A glass bottle with secondary thermo-packaging (carton tote with a polyethylene (PE) film)
- A glass bottle with secondary wrap packaging (corrugated carton)
- A plastic bottle with secondary wrap packaging (corrugated carton)
- A plastic bottle with secondary strapping packaging (PP strapping)
- A recycled plastic bottle with secondary wrap packaging (corrugated carton)
- A recycled plastic bottle with secondary strapping packaging (PP strapping)

End-of-life disposal was incineration, recycling and landfill disposal. The functional unit was a 1 litre bottle of EVOO (i.e. equal to 0.916 kg/litre), including the EVOO content, its primary, secondary and tertiary packaging. The supply chain processes involved included the supply of EVOO from Spain and Greece to the bottling facility in Italy (cultivation of olives excluded), the supply of packaging from the producers to the bottling facility, the EVOO consolidation and processing, the bottling and packaging, the storage and distribution to customers worldwide, and the end-of-life treatments of the packaging waste. An attributional LCA of the packaging scenarios was followed by a consequential LCA to evaluate the uncertainty in the EOL strategies and associated input/output flows in different countries. The consequential LCA compares the impacts associated with the evaluated scenarios in response to purchasing, policy or technological decisions.

The main parameters of the study and an overview of the results are given in Table B27.

Summary of results and conclusions

At recycling rates above 40% EVOO in a glass bottle has a lower climate impact than EVOO in a PET bottle. This is despite EVOO in glass bottles having higher impacts than EVOO in PET up until packaging end-of-life.

If a recycled content of 50% was possible (currently not the case in Italy) then the rPET bottle would be the environmentally preferred option.

Findings include:

- The bottling and packaging phases contributed significantly to the global warming impacts of packaged EVOO, with the highest contributions in the glass bottles.
- The glass bottles also had the highest impact for the acidification and photochemical oxidation impacts, primarily a consequence of the bottling process.
- EOL has a significant effect on the overall ranking of the different packaging solutions. The consequential analysis showed that at recycling rates greater than 40%, the glass bottle has lower climate change impacts than the PET bottle.

Table B27: Summary table: Accorsi, Versari and Manzini (2015)

		Products considered in study					
		Glass bottle with thermo-packaging	Glass bottle with wrap packaging	Plastic bottle with wrap packaging	Plastic bottle with strapping packaging	Recycled plastic bottle with wrap packaging	Recycled plastic bottle with strapping packaging
Study scope	**Materials**	Glass; aluminium and PE (cap and pourer); cardboard with PE film (secondary packaging)	Glass; aluminium and PE (cap and pourer); cardboard (secondary packaging)	PET (bottle, cork and heat-shrink sleeve); cardboard (secondary packaging)	PET (bottle, cap and heat-shrink sleeve); PP (secondary packaging)	rPET (bottle), PET (cap and heat-shrink sleeve); cardboard (secondary packaging)	rPET (bottle), PET (cap and heat-shrink sleeve); PP (secondary packaging)
	Functional unit (FU)	1 litre bottle of EVOO (i.e. equal to 0.916 kg/litre), including the EVOO content, its primary, secondary and tertiary packaging.					
	Number per FU	1					
	Weight per FU	Bottle: 460 g Thermopack: 9.33 g	Bottle: 460 g Wrap: 20.4 g	Bottle: 36 g Wrap: 20.4 g	Bottle: 36 g Strapping: 0.75 g	Bottle: 36 g Wrap: 20.4 g	Bottle: 36 g Strapping: 0.75 g
	Geographic region	Bottling in Italy (EVOO supply from Spain and Greece) with distribution worldwide					
	Life cycle stages	Supply of EVOO from the production areas (excluding cultivation); consolidation of EVOO at the bottling facility; supply of packaging and auxiliary materials; bottling and processing; storage and distribution processes; and EOL treatments (both the consumer waste and the waste generated at the production facility)					
	Use phase assumptions	N/A					
	End of life assumptions	Attributional LCA: average European fractions of urban waste devoted to recycling, incineration and landfill; Consequential LCA: multi-scenario analysis varying percentages of glass and PET to recycling					
	Global warming	🟨	🟨	🟥	🟨	🟨	🟩
	Non-renewable resource depletion	🟥	🟥	🟨	🟨	🟨	🟩
	Eutrophication	🟨	🟨	🟥	🟨	🟨	🟩
	Acidification	🟥	🟥	🟩	🟩	🟩	🟩
	Phoochemical oxidation	🟥	🟥	🟥	🟥	🟩	🟩
	Ozone layer depletion	🟥	🟥	🟨	🟩	🟨	🟨
Method	Environmental Design of Industrial Products (EDIP) 2003						
Data and software	Ecoinvent version 2.2 and SimaPro version 7.18						
Reviewed	Peer-reviewed journal article						

APPENDIX B

Comparative Life Cycle Assessment of Packaging Systems for Extended Shelf Life Milk: Bertolini *et al*. (2016)

The aim of this study was to compare the environmental impact of different packaging systems used for extended shelf life (ESL) milk in Italy. Three different packaging options were considered:

- PET bottle with PVC shrink-sleeve label, 12 bottles wrapped together with shrink film
- HDPE bottle with PVC label, 12 bottles wrapped together with shrink film
- Multi-layer carton, 10 cartons placed in cardboard box

Milk is packaged and consumed in Italy, with caps sourced from Sweden and LDPE granulate sourced from Belgium. The end-of-life assumptions were recycling, landfill and incineration with energy recovery. The functional unit of the study was the packaging required to contain 1 litre of extended shelf life milk with a guaranteed shelf life of 30 days. Included in the LCA were the extraction of packaging raw materials, the resin production, the container formation, the filling of the ESL milk, the end-of-life of packaging materials, transport activities, and the production of caps, labels, and secondary packaging such as film and boxes. The transport activities incorporated the shipping and road transport of raw materials, packaging materials and packaged products.

The main parameters of the study and an overview of the results are given in Table B28.

Summary of results and conclusions

The **environmental impacts of ESL milk in multi-layer cartons are, on average, more than 12% lower than that in HDPE bottles and more than 34% lower than that in PET bottles with shrink sleeve labels.**

Findings include:

- For the PET packaging, bottle production is the most significant stage, contributing 52 to 79% across the impact categories. Production of the cap also has a significant contribution (contributing 11 to 38% across the impact categories). Transport has a relatively low contribution to impacts (1 to 4%), whilst the filling process accounts for 5 to 10% across the impacts. The end-of-life processes decrease the overall impacts due to the energy recovered from packaging incineration and from recycling.
- For the HDPE packaging, bottle production also has the highest contribution across the impact categories, ranging from a 34% to 80%. The cap contributes 3 to 26% across the impact categories, the label 1 to 10%, and the ultra-clean filling system 7 to 14%. Contributions from transport are relatively small. Recycling and energy recovery at end-of-life results in decreases in the environmental impacts.
- For the multi-layer carton, the primary packaging materials and beverage carton converting account for greater than 23% across all impact categories. For the carton system, the other stages (notably transport) and production of other packaging components (especially the cap) have higher contributions than seen for the plastic bottles. This is because the impacts of carton production are low relative to bottle production. End-of-life decreases due to recycling and energy recovery are less significant for the cartons than for the bottles. Carton end-of-life processes contributes 29% to global warming potential.
- The multi-layer carton has lower impacts than the other packaging solutions across most impact categories. The only exceptions are ozone depletion potential and eutrophication potential, in which the HDPE packaging has the lowest impacts. For all other impacts, the differences between the multi-layer carton and the plastic packaging systems are significant, ranging between 16% lower for acidification potential to 42% lower for human toxicity potential.
- The HDPE packaging has lower impacts across most categories than the PET packaging.

Table B28: Summary table: Bertolini *et al.* (2016)

		Products considered in study		
		PET bottle with shrink sleeve label	**HDPE bottle**	**Multi-layer carton**
Study scope	Materials	PET (bottle), HDPE (cap), PVC (shrink sleeve), PE (shrink film)	HDPE with TiO_2 layer (bottle), PP (cap), PVC (label), PE (shrink film)	Carton (paperboard and LDPE), HDPE (cap), cardboard (box)
	Functional unit (FU)	1 litre of extended shelf life milk with a guaranteed shelf life of 30 days		
	Number per FU	1	1	1
	Weight per FU (g)	PET bottle: 25.2; HDPE cap: 3.5; PVC shrink sleeve: 4.75; PE film: 0.24	HDPE bottle: 31.6; PP cap: 3.5; PVC label: 0.8; PE film: 0.24	Laminated carton: 6.8 (LDPE), 25.5 (paperboard); HDPE Cap: 4.3; Cardboard box: 7.34
	Geographic region	Italy, with caps sourced from Sweden and LDPE granulate sourced from Belgium		
	Life cycle stages	Cradle-to-grave (packaging raw materials, container formation, filling of ESL milk, end-of-life of packaging materials and transport activities)		
	Use phase assumptions	N/A		
	End of life assumptions	Plastic: 37.9% recycled, 44.5% energy recovery, 17.5% landfill; Paper: 79.3% recycle, 8.63% energy recovery, 11.85% landfill		Carton, paperboard: 19% recycle, 22% energy recovery, 59% landfill; Carton, other materials: 25% energy recovery, 75% landfill
Indicators	**Cumulative energy demand**	🟥	🟥	🟩
	Global warming potential	🟥	🟥	🟩
	Photochemical ozone creation potential	🟥	🟨	🟩
	Stratospheric ozone depletion potential	🟥	🟩	🟨
	Human toxicity potential	🟥	🟥	🟩
	Acidification potential	🟥	🟨	🟩
	Eutrophication potential	🟥	🟩	🟨
Method	CML2001 and cumulative energy demand (CED)			
Data and software	SimaPro version 7.3.3, Plastics Europe Database, ELCD database 2.0, US LCI Database, Ecoinvent database v 2.2			
Reviewed	Peer-reviewed journal article			

Exploring the Environmental Impacts of Olive Packaging Solutions for the European Food Market: Bertoluci, Leroy and Olsson (2014)

The aim of this study was to compare the environmental performance an olive packaging system across five different European countries (France, Germany, Italy, Spain and Sweden), as well as to assess the influence of consumer preference and behaviours on packaging performance. A series of five LCAs were performed on three different types of olive packaging:

- Glass jars with a metal lid and an inner coating of resin,
- Steel cans made of electrolytic chrome coated steel (ECCS),
- Doypacks (multi-layered plastic stand-up pouches) made of PE and PET

The end-of-life scenarios that were considered in the five countries were landfill, incineration with energy recovery and recycling.

APPENDIX B

The main parameters of the study and an overview of the results are given in Table B29.

Summary of results and conclusions

It is important to increase waste collection rates and recycling in order to decrease the environmental impacts of packaging. Furthermore, eco-design of packaging cannot only consider the types of materials employed. **Consumer behaviour, and especially how consumer behaviour relates to increased food waste, is as important a criterion to consider as material type.**

Findings include:

- The **glass jar has the highest impacts despite its high rate of recycling** in the five countries. The energy mix in the country is influential in the glass jars' high impacts. Thus, only in Sweden, where the energy mix is 50% nuclear, does the steel can have higher impacts than the glass jar in some impact categories.
- The **multi-layered plastic stand-up pouch (doypack) has the lowest potential impacts in climate change, human toxicity, particulate matter formation and ionizing radiation across all five countries despite it being non-recyclable**. The better performance of Doypacks in Germany relative to the other countries is because of their 100% collection and incineration with energy recovery in Germany (thereby avoiding energy production from coal).
- The **doypack is shown to be least preferred in a functional analysis**, and associated with an increased number of olives thrown away.

Table B29: Summary table: Bertoluci, Leroy and Olsson (2014)

		Products considered in study		
		Glass jar	**Steel can**	**Doypack (multi-layered plastic stand-up pouch)**
Study scope	Materials	Glass (jar), electrolytic chrome coated steel (ECCS) (lid), epoxy resin, corrugated board (secondary packaging)	Electrolytic chrome coated steel (ECCS) (can), epoxy resin, corrugated board (secondary packaging)	LDPE and PET (multi-layer pack), corrugated board (secondary packaging)
	Functional unit (FU)	Packaging of one tonne of olives for aperitif and cooking usage		
	Number per FU	6250	5555.5	9345.8
	Weight per FU (g)	178 g: glass 170 g (jar), ECCS 7.9 g (lid), epoxy resin 0.1 g	57 g: ECCS 56.3 g, epoxy resin 0.67 g	5 g: LDPE 3.75 g, PET 1.25 g
	Geographic region	France, Germany, Italy, Spain and Sweden		
	Life cycle stages	Cradle-to-grave (packaging raw materials preparation; the primary, secondary, and tertiary packaging production; transportation from the production plant to retailers, and from retailers to consumers; and the waste management processes). Olive production is excluded.		
	Use phase assumptions	N/A		
	End of life assumptions	Country-specific collection and recycling rates for glass, metal, plastic, cardboard and wood.		France, Italy and Spain: ends up in domestic waste stream (not sorted); Sweden: 50% sorted and incinerated; Germany 100% sorted and incinerated

Table B22: Continued – Summary table: Bernstad Saraiva *et al*. **(2016)**

		Products considered in study		
		Glass jar	Steel can	Doypack (multi-layered plastic stand-up pouch)
Indicators		**Germany**		
	Climate change human health	🟥	🟨	🟩
	Human toxicity	🟥	🟨	🟩
	Particulate matter formation	🟥	🟨	🟩
	Ionising radiation	🟥	🟨	🟩
	Fossil depletion	🟥	🟨	🟩
		Spain		
	Climate change human health	🟥	🟨	🟩
	Human toxicity	🟥	🟨	🟩
	Particulate matter formation	🟥	🟨	🟩
	Ionising radiation	🟥	🟨	🟩
	Fossil depletion	🟥	🟩	🟩
		France		
	Climate change human health	🟥	🟨	🟩
	Human toxicity	🟥	🟥	🟩
	Particulate matter formation	🟥	🟨	🟩
	Ionising radiation	🟥	🟨	🟩
	Fossil depletion	🟥	🟩	🟩
		Italy		
	Climate change human health	🟥	🟨	🟩
	Human toxicity	🟥	🟨	🟩
	Particulate matter formation	🟥	🟨	🟩
	Ionising radiation	🟥	🟩	🟩
	Fossil depletion	🟥	🟩	🟩
		Sweden		
	Climate change human health	🟨	🟥	🟩
	Human toxicity	🟨	🟥	🟩
	Particulate matter formation	🟥	🟨	🟩
	Ionising radiation	🟥	🟥	🟩
	Fossil depletion	🟩	🟩	🟥
Method	ReCiPe version 1.03			
Data and software	Ecoinvent version 2.0 and SimaPro version 7			
Reviewed	Peer-reviewed journal article			

APPENDIX B

Environmental Analysis along the Supply Chain of Dark, Milk and White Chocolate: A Life Cycle Comparison: Bianchi *et al*. (2021)

This LCA assessed the environmental impacts of dark, milk and white chocolate manufactured in Italy, including an assessment of three packaging materials:

- Polypropylene wrapper
- Aluminium foil and cardboard
- Aluminium foil and paper

A summary of the main study parameters (looking just at the packaging assessment and not the wider chocolate study) is given in Table B30.

Summary of results and conclusions

Packaging impacts are relatively small within the context of the chocolate product, with by far the main source of environmental impacts the chocolate raw materials, in particular the dairy and cocoa derivatives. Nonetheless, the **plastic wrapper is the best packaging option by a considerable margin.**

- The polypropylene (PP) wrapper has the lowest environmental impacts in all impact categories considered by a significant margin (with impacts 60%–98% lower than the foil and cardboard).
- The higher impacts of the aluminium foil and cardboard/paper are primarily a result of the production of the aluminium foil.
- The aluminium foil plus cardboard is the least environmentally preferred of the three options considered.

Table B30: Summary table: Bianchi *et al*. (2021)

		Products considered in study		
		PP wrapper	Aluminium foil and cardboard	Aluminium foil and paper
Study scope	**Materials**	Single layer of 100% polypropylene	Aluminium foil; cardboard	Aluminium foil; kraft paper
	Functional unit (FU)	1 kg of chocolate		
	Weight per FU [grams]	20 g	Aluminium 18 g, cardboard 118 g	Aluminium 18 g, paper 24 g
	Geographic region	Italy		
	Life cycle stages	"cradle to grave" (raw material production (cocoa, milk powder, sugar and product packaging), cocoa transport, chocolate manufacturing and packaging waste management)		
	Use phase assumptions	n/a		
	End of life assumptions	12.5% landfilled, 43% incinerated, 44.5% recycled	Foil: 13.4% landfilled, 6.4% incinerated, 80.2% recycled. Cardboard and paper: 11.2% landfilled, 7.7% incinerated, 81.1% recycled.	
Indicators	Acidification potential	🟩	🟥	🟨
	Eutrophication potential	🟩	🟥	🟨
	Global warming potential	🟩	🟥	🟨
	Photochemical oxidant creation potential	🟩	🟥	🟨
	Abiotic depletion–elements	🟩	🟥	🟨
	Abiotic depletion–fossil fuels	🟩	🟥	🟨
	Water use	🟩	🟥	🟨
	Cumulative energy demand	🟩	🟥	🟨
Method	CML 2001 other than POCP (ReCiPe 2008), net water use and CED			
Data and software	ecoinvent database; SimaPro software			
Reviewed	Peer-reviewed journal article			

Comparative Carbon Footprint of Packaging Systems for Tuna Products: Poovarodom, Ponnak and Manatphrom (2012)[28]

The aim of this study was to evaluate and compare the carbon footprint associated with canned tuna meat, with a focus on single-serving packaging systems. The study looked at three different ways of packaging a single serving of tuna:

- Two-piece chrome-coated steel can with an aluminium pull ring tab
- Multi-layer plastic retort pouch
- Plastic (PP/EVOH) retort cup with multi-layer plastic lid

The “single serving” amount varies between the different forms of packaging. The can has a net weight of 85 g and a drained weight of 65 g, the retort pouch has a net weight of 85 g and a drained weight of 75 g, and the retort cup has a net weight of 80 g and a drained weight of 61 g of tuna.

The study takes into account the tuna fishery, tuna meat production, raw materials and production of the cans, retort pouches, and retort cups, as well as the processing of the tuna into the packaging, the disposal of the packaging and the transport required between each of the stages. The study does not take into account the consumption or possible wastage of the tuna by the buyer.

A summary of the main study parameters is given in Table B31.

Summary of results and conclusions

The **overall carbon footprint of canned tuna in retort cups was 10% and 22% less than when packaged in metal cans and retort pouches**, respectively.

Packaging and its associated processing constitute a significant fraction of the life cycle carbon footprint of a single serving of tuna, ranging from 20% to 40%. The tuna meat production constitutes the greatest share of emissions.

Findings include:

- For cans, the manufacture of the packaging produces the second-highest emissions (after tuna meat production), with the transport, packaging and processing stages having only a small share of emissions by comparison. The GHG emissions from can manufacturing (104 gCO2eq./functional unit) are considerably higher than those of the pouch and cup (at 43 and 33 gCO2eq./functional unit for pouch and cup production, respectively).
- For pouches, the manufacture of the packaging, as well as the processing stage, are both significant contributors to carbon footprint. Emissions from the processing stage for the pouches is considerably higher than that of the can and cup.
- For cups, the manufacture of the packaging products and the processing stage have similar carbon footprints, resulting in the lowest overall carbon footprint (253 g CO2 eq./functional unit compared 280 g CO2 eq./functional unit for the cans and 322 g CO2 eq./functional unit for the pouches).
- Regards end-of-life processing, the incineration of the retort cups has the highest carbon footprint (2.2 g CO2 eq./functional unit), whereas recycling of the cans has in the lowest carbon footprint (-37.25 g CO2 eq./functional unit).

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[28] This study is included in the meta-analysis even though it does not fully meet the selection criteria (it considers only climate impact) because of the very few studies from a developing country context.

APPENDIX B

Table B31: Summary table: Poovarodom, Ponnak and Manatphrom (2012)

		Products considered in study		
		Can	Retort pouch	Retort cup
Study scope	**Materials**	Chrome-coated steel (can), aluminium (pull ring tab)	PP/Al/ON/PP	PP/EVOH/PP (cup) PET/Al/ON/PP lids
	Functional unit (FU)	Commercially available unit package designed for one single serving		
	Weight per FU [grams]	1	1	1
	Geographic region	Thailand, with consumption in the UK		
	Life cycle stages	Cradle-to-grave, including tuna production		
	Use phase assumptions	N/A		
	End of life assumptions	Steel: 35.48% landfill; 7.22% incinerated; 57.30% recycled Plastics: 64.90% landfill; 13.20% incinerated; 21.90% recycled Paper: 18.86% landfill; 3.84% incinerated; 77.30% recycled		
Indicators		🟨	🟥	🟩
Method	CML 2 Baseline 2000 (GWP time horizon of 100 years)			
Data and software	Buwal 250 and Ecoinvent database			
Reviewed	Peer-reviewed journal article			

Reuse of Honey Jars for Healthier Bees: Developing a Sustainable Honey Jars Supply Chain through the Use of LCA: Postacchini *et al.* (2018)

This study aims to improve the sustainability of an existing honey production supply chain by evaluating the potential for changing from the current single-use glass jar system to a returnable glass jar system.

A summary of the main study parameters is given in Table B32.

Summary of results and conclusions

The returnable glass jar system was found to have considerably lower climate and ecosystem impacts than a single-use jar system in the distribution of honey in Italy. With an optimized reverse logistics supply chain (i.e. a logistics centre for collecting and distributing jars in each municipality and a washing/packaging centre at the honey consortium's headquarters), the **change to returnable glass jars could reduce environmental impacts by more than 70% (on average) over five years**. These high reductions in impacts were for an assumed reuse rate of 85%, and compared to single-use jars collected by curb-side collection and recycled at end-of-life. However, the optimized reuse supply chain was found to have environmental benefits even when only 10% of the glass jars were assumed returned, with the potential to reduce environmental impacts by 18% to 22% over five years.

Table B32: Summary table: Postacchini *et al.* (2018)

		Products considered in study	
		Single-use glass jar	**Reusable glass jar**
Study scope	**Materials**	Glass (61% recycled content)	Glass (61% recycled content)
	Functional unit (FU)	The packaging of 300 metric tonnes of honey a year, over a time period of 5 years	
	Number per FU	300,000 x 5	300,000 in the first year, followed by 45,000 in the subsequent four years
	Weight	323.7 g	
	Geographic region	All activities, including glass production and recycling, take place in the Macerata province of Italy	
	Life cycle stages	Full life cycle of the jars excluding labels and caps	
	Use phase assumptions		85% reuse factor (i.e. 15% non-returned or broken). Centralized washing process includes soaking in hot water (label removal) followed by washing in industrial dishwasher. Energy used in heating water and in dishwasher included, soap use excluded.
	End of life assumptions	Curb-side recycling (assuming no losses)	
Indicators	Aquatic ecotoxicity	🟥	🟩
	Terrestrial ecotoxicity	🟥	🟩
	Terrestrial acid/nutri	🟥	🟩
	Land occupation	🟥	🟩
	Global warming	🟥	🟩
Method	IMPACT 2002 + (selected indicators)		
Data and software	Ecoinvent v3.3 database, other than electricity, which is taken from ELCD		
Reviewed	Peer-reviewed journal article		

Analyzing the Packaging Strategy of Packaging-Free Supermarkets: Scharpenberg *et al.* (2021)

The goal of this study is to clarify the potential environmental advantages of packaging-free supermarkets. In so doing, the authors conduct a **comparative LCA of six products retailed at the German packaging-free supermarket Original Unverpackt (OU) relative to conventionally packaged products** sold in small organic food stores. The products assessed are chia seeds, fruit bears, noodles, tofu, dishwashing shower gel and detergent[29].

The tofu product is sold in returnable glasses at Original Unverpackt. The returnable glasses are compared to tofu sold in single-use LDPE bags.

The functional unit applied in the comparison is the quantity of packaging material needed to transport and provide one unit of the conventionally packaged product, and one unit of the "packaging-free" product in its typical container size. The system boundary thus includes all primary, secondary and transport packaging, as well as the transport of the packaged product to the store. The product itself is excluded. For both the bulk- and conventionally-packaged products, all packaging is assumed to be discarded after use (either recycled, incinerated or landfilled, in accordance with the prevailing practices for that material type in Germany). The packaging-free system includes the cleaning of the returnable glasses.

A summary of the main study parameters is given in Table B33.

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[29] Only the four food products are covered in the meta-analysis, given the focus of the report is on food packaging. The tofu product is covered here with chia seeds, fruit bears and noodles (dispensed products) covered in the next sub-section.

APPENDIX B

Summary of results and conclusions

Selling tofu in returnable glasses did not show any environmental benefits relative to tofu sold in conventional plastic packaging. The higher greenhouse gas emissions of the glass packaging result primarily from the production of the glass (due to the relatively low return rate of glasses) and its transport. The packaging-free tofu system analysed might be considered somewhat atypical in that Tofu is supplied by a small local supplier, with the tofu product transported to store in a passenger car.

Table B33: Summary table: Scharpenberg *et al*. (2021)–Tofu

		Products considered in study: Tofu packaging	
		Reusable glass	Plastic bag
Study scope	**Materials**	White glass with tinplate cap	LDPE
	Functional unit (FU)	The quantity of packaging material needed to transport and provide one unit of the conventionally packaged counterpart of the “packaging-free” product in its typical container size.	
	Number per FU	1 x 200g pack	
	Weight	234 g white glass; 14 g tinplate (cap)	5 g LDPE; 28,75 g corrugated cardboard; 0.12 g LDPE stretch film
	Geographic region	Germany	
	Life cycle stages	Cradle-to-grave, including the raw materials and production of all packaging (primary, secondary and tertiary), transport of packaging, use phase (washing and transport of reusable containers)	
	Use phase assumptions	Water, energy and detergent used in washing reusable containers are included. Reusable containers are assumed to be washed after every use	N/A
	End of life assumptions	The shares of packaging materials incinerated, recycled or landfilled are according to German packaging ordinances. Recycled material substitutes raw material, with recycled material generally allocated by 50%. No energy credits are given.	
Indicators	**Agricultural land occupation**	🟥	🟩
	Urban land occupation	🟥	🟩
	Fossil depletion	🟥	🟩
	Ionizing radiation	🟥	🟩
	Resource depletion	🟥	🟩
	Human toxicity	🟥	🟩
	Climate change	🟥	🟩
	Water depletion	🟥	🟩
Method	ReCiPe Midpoint (Hierarchist) without long term.		
Data and software	Umberto NXT software and Ecoinvent v. 3.1 database		
Reviewed	Peer-reviewed journal article		

B.3.2 Dry goods

Life Cycle Assessment of Waste Prevention in the Delivery of Pasta, Breakfast Cereals, and Rice: Dolci *et al*. (2016)

This study uses LCA to evaluate the potential environmental benefits of loose distribution compared with conventional distribution with single-use packaging. Self-dispensing systems whereby consumers are able to dispense the amount of product they wish to purchase from gravity bin dispensers at the retail store is being put forward as a potential solution to decrease the packaging waste associated with food supply chains. In this study the most common single-use packaging solutions for dry pasta, breakfast cereals and rice in Italy are compared with a loose distribution system. For each of the products, a loose distribution system currently employed in a supermarket in Italy is evaluated, along with two other scenarios looking at potential improvements (changing the primary packaging used to refill the gravity dispenser in store).

For dry pasta, three commonly-used single-use packaging systems were included in the study, each available as 500 g or 1 kg packs:
- PP pillow bag
- PP double square bottom (dsb) bag
- Cartonboard box (primary packaging)

In the evaluation of the loose distribution system, three primary packaging options (the packaging used to transport pasta from the manufacturer to the gravity bin at the retail store) were looked at, namely:
- 1 kg PP pillow bag
- 3 kg PP pillow bag
- 5 kg LDPE pillow bag

In both distribution systems, primary packages are placed in corrugated cardboard boxes, placed on wooden pallets and wrapped with LLDPE stretch film.

In the purchase of the loose pasta, either an LDPE bag or a cellulose bag is assumed to be used by the consumer, with either 500 g of 1 kg of pasta drawn from the dispenser (chosen to match the single-use packaging sizes).

For breakfast cereals, four sizes of the traditional bag-in-box cereal packaging were covered in the study. The bag-in-box packaging consists of an HDPE bag placed inside a cartonboard box. The sizes evaluated were 300 g, 375 g, 500 g and 960 g. The primary packages are placed in corrugated cardboard boxes, placed on wooden pallets and wrapped with LLDPE stretch film.

The loose distribution system for breakfast cereals consists of 10 kg paper sacks (primary packaging), transported on wooden pallets and wrapped in LLDPE stretch film. Consumers are assumed to use an LDPE bag for the purchase of loose breakfast cereal, with the amount of cereal drawn from the gravity dispenser coinciding with the amount in the single-use packaging options (i.e. 300 g, 375 g, 500 g or 960 g) for comparative purposes.

For rice, eight traditional bag-in-box packaging scenarios were included in the study, covering different pack sizes, and different primary and transport packaging options, as follows:
- Mixed plastic bag inside a cartonboard box; boxes wrapped in an LDPE heat-shrink film (1 kg and 2 kg pack sizes)
- Mixed plastic bag inside a cartonboard box, boxes placed in a corrugated cardboard box (1 kg pack size)
- Mixed plastic bag; bags wrapped by an LDPE heat-shrink film or placed in a corrugated cardboard box (1 kg pack size)
- Two 1 kg mixed plastic bags wrapped together by LDPE heat-shrink film; wrapped bags placed in a corrugated cardboard box (2 kg pack size)
- Cartonboard box, boxes wrapped in an LDPE heat-shrink film or placed in a corrugated cardboard box (1 kg pack size)

In the evaluation of the loose distribution of rice, three primary packaging options were looked at, namely:
- 2 kg LDPE pillow bag, wrapped in LDPE heat-shrink film
- 5 kg LDPE pillow bag, wrapped in LDPE heat-shrink film
- 25 kg raffia sack (no transport packaging)

In both rice distribution systems, transport packages are placed on wooden pallets and wrapped with LLDPE stretch film.

In the purchase of loose rice, an LDPE bag was assumed to be used by the consumer, with either 1 kg or 2 kg of rice drawn from the dispenser (chosen to match the single-use packaging sizes).

The functional unit is the distribution of 1 kg of food product (dry pasta, breakfast cereals or rice).

Across all three dry food products, the comparison between the traditionally packaged product and the self-dispensed product is made on the purchase of an equivalent amount of product. Potential savings in food waste due to customers being able to purchase only the amount of product they require is therefore not evaluated. The potential for customers to reuse bags or bring their own containers when purchasing loose product is also not evaluated in the study.

The system boundary includes the manufacture and disposal of all packaging, the food packaging operations, the transport of the packaged product to retail, and the return trip with empty pallets. For the loose distribution system, the system boundary also includes the bag used for the purchase of loose product and the manufacture and end-of-life disposal of the gravity bin dispenser (made of polycarbonate). The dry food product itself is excluded, as is transport from retail to the point of consumption.

The study aims to evaluate the current situation in Italy. Primary packaging was assumed to be manufactured from virgin raw materials, except for the cartonboard boxes which are mainly produced from recycled pulp (depending on the producer information provided). All primary packaging, other than mixed plastic bags and bulk sacks, are assumed to be collected, sorted and recycled. The waste management system modelled is that of Northern Italy, using data on collection, sorting and recycling specific to this region for primary packaging and ecoinvent for transport packaging. Recycling was modelled with avoided production; plastic lumber made from recycled plastic bags and shrink films are assumed to replace wooden planks. Secondary pulp from recycled cartonboard boxes were assumed to replace virgin pulp (allowing for the degradation of fibre quality in the assumed replacement rate). Mixed plastic bags and cellulose bags were assumed to be incinerated in a waste-to-energy plant, with electricity (Italian grid mix) and thermal energy from methane boilers the avoided products. Corrugated cardboard boxes were assumed to be manufactured from recycled pulp and fully recycled after use into corrugate board base paper.

Summary of results and conclusions

Whether or not loose distribution is environmentally preferred depends on the food type and particularly on the single-use packaging used for the food product. The **loose distribution system was shown to have notably lower impacts than bag-in-box type single-use packaging**, e.g. as commonly used for breakfast cereals. However, **where the food is packed only in a plastic bag, e.g. dry pasta, the loose distribution not only shows no environmental benefits but can even increase impacts and waste generation.**

Dry pasta

Table B34 summarizes the dry pasta case study and provides an overview of the results for the best-performing traditional single-use packaging (1 kg pillow bag) compared with the three loose distribution scenarios.

- **Loose distribution of dry pasta was found to not always decrease packaging waste and environmental impacts relative to traditional packaging.** The scenario in which dispensers were filled using a 1 kg bag was shown to increase packaging waste by 13% relative to the best-performing single-use packaging scenario (the 1 kg pillow bag). This is because of the additional plastic bag used by the consumer when purchasing the loose dry pasta.
- Loose distribution of dry pasta was found to decrease packaging waste and environmental impacts when dispensers are filled with 2 kg and 3 kg bags, but decreases were found to be slight (10% or less, with differences in impacts less than 10% considered not to be significant as they are within the uncertainty range of the LCA).
- Bigger decreases in packaging waste and environmental impacts were observed where the loose distribution system replaces dry pasta packaged in double square-bottom bags or cartonboard boxes. The best-performing loose distribution scenario (3 kg bags) results in 49% less packaging waste than the worst-performing traditional packaging (cartonboard box), with reductions in impacts of between 12% and 65%. It is however worth noting that these reductions in waste and impacts are more or less the same as the differences between the best- (1 kg pillow pack) and worst-performing (1 kg box) single-use packaging options.

Breakfast cereals

Table B35 summarizes the breakfast cereals case study and provides an overview of the results of the loose distribution scenario versus various sizes of traditional breakfast cereal boxes.

- The loose distribution of breakfast cereals is preferable to that in single-use packages across all environmental indicators. The **loose distribution of breakfast cereals decreases packaging waste by up to 84%** when compared with traditional bag-in-box single-use packaging, and **decreases environmental impacts by 39% to 83%,** depending on the impact indicator and packaging size.
- The lower packaging waste and impacts of the loose distribution system is a consequence of the change in packaging, with the bag-in-box packaging having a mass per kg cereal distributed an order of magnitude higher than the bulk paper sack (used in the loose distribution).
- Self-dispensing 500 g results in the least packaging waste, owing to the fact that a consumer must use two LDPE bags when dispensing 960 g (whilst only one bag is needed for 500 g). However, the smaller the bag-in-box size, the greater the packaging mass per kg of cereal distributed. The greatest reduction in packaging waste and environmental impacts is thus for the 300 g scenario, with the 960 g scenario showing the least reductions (although these are still notable).

Rice

Table B36 summarizes the rice case study and provides an overview of the results for the baseline traditional single-use packaging (1 kg pillow bag with cardboard box as transport packaging) compared with the three loose distribution scenarios.

- **All the loose distributions scenarios generate less packaging waste and lower environmental impacts than the traditional single-use packaging of rice** on the Italian market (with the exception of ozone depletion in the 1 kg bag scenario).
- **Rice packaged in bag-in-box type packaging and cartonboard boxes generate substantially more packaging waste and environmental impacts than rice packaged in a plastic bag.** The reductions in packaging waste when switching from traditional to loose distribution are thus greatest when the change is from rice packaged as a bag-in-box or in a cartonboard box. For example, reductions ranging from 53% to 83% occur in all fourteen indicators for the case of the 1 kg bag-in-box scenario. The decrease in packaging waste from rice packaged in a plastic bag is smaller but still notable at 30%.
- Self-dispensing 2 kg of rice, with the dispenser filled using a 5 kg LDPE bag results in the least packaging waste (with the dispenser filled with a 2 kg bag generating only marginally more waste). In general, the environmental impacts of loose distribution decrease as the size of the packaging used to refill the dispensers increases. Thus the 25 kg sack loose distribution system has the lowest environmental impacts, other than for climate change and human toxicity (cancer effects), for which the scenario with the 5 kg bag has the lowest impacts.

APPENDIX B

Table B34: Summary table: Dolci *et al*. (2016)- Dry Pasta

		Best-performing single-use packaging: 1 kg pillow bag	Loose distribution (self-dispensing system)		
			1 kg bag	3 kg bag	5 kg bag
Study scope	**Materials**	PP pillow bag; corrugated cardboard box transport packaging	Dispenser filled from 1 kg PP bag, corrugated cardboard box transport packaging; Consumers purchase product in LDPE bag	Dispenser filled from 3 kg PP bag, corrugated cardboard box transport packaging; Consumers purchase product in cellulose bag	Dispenser filled from 5 kg PP bag, corrugated cardboard box transport packaging; Consumers purchase product in LDPE bag
	Functional unit (FU)	The distribution of 1 kg of dry pasta			
	Geographic region	Italy			
	Life cycle stages	Full life cycle of all packaging, packaging operations and transport to retail	Full life cycle of all packaging (cradle to grave), packaging operations, transport to retail, and full life cycle (cradle to grave) of the gravity bin dispenser		
	Use phase assumptions	n/a	Dispensers filled 3 times a week		
	End of life assumptions	All primary packaging separately collected, sorted and recycled, other than cellulose bags which are incinerated (with energy recovery). End-of-life modelling represents the situation in Northern Italy (67% curbside collection, 33% street containers).			
Indicators	**Climate change**	🟩	🟥	🟩	🟨
	Ozone depletion	🟨	🟥	🟩	🟨
	Photochemical ozone formation	🟩	🟥	🟩	🟨
	Acidification	🟩	🟥	🟩	🟨
	Terrestrial eutrophication	🟩	🟥	🟩	🟨
	Freshwater eutrophication	🟨	🟥	🟩	🟨
	Marine eutrophication	🟩	🟥	🟩	🟨
	Freshwater ecotoxicity	🟨	🟥	🟩	🟨
	Human toxicity (cancer effects)	🟩	🟥	🟩	🟨
	Human toxicity (noncancer effects)	🟨	🟥	🟨	🟩
	Particulate matter	🟩	🟨	🟥	🟨
	Water resource depletion	🟩	🟥	🟨	🟨
	Mineral and fossil resource depletion	🟨	🟥	🟩	🟨
	Cumulative energy demand	🟩	🟥	🟩	🟨
Method	Characterization methods recommended by the Joint Research Centre of the European Commission, other than for mineral and fossil resource depletion which is on the basis of the "ultimate reserves" of resources. Cumulative energy demand was also calculated.				
Data and software	Ecoinvent database and SimaPro software				
Reviewed	Peer-reviewed journal article				

Table B34: Continued – Summary table: Dolci *et al*. **(2016)- Dry Pasta**

Table B35: Summary table: Dolci *et al*. (2016)- Breakfast cereal

		Products considered in study: BREAKFAST CEREAL				
		Traditional distribution (bag-in-box single-use packaging)				Loose distribution
		300 g	375 g	500 g	960 g	
Study scope	**Materials**	HDPE bag placed inside a cartonboard box; corrugated cardboard box as transport packaging				Dispenser filled from 10 kg paper sack; wooden pallet and LLDPE stretch film as transport packaging ; Consumers purchase product in LDPE bag
	Functional unit (FU)	The distribution of 1 kg of breakfast cereal				
	Geographic region	Italy				
	Life cycle stages	Full life cycle of all packaging (raw materials to disposal), packaging operations, and transport to retail				Full life cycle of all packaging (cradle to grave), packaging operations, transport to retail, and full life cycle (cradle to grave) of the gravity bin dispenser
	Use phase assumptions	n/a				Dispensers filled 3 times a week
	End of life assumptions	All primary packaging separately collected, sorted and recycled, other than cellulose bags which are incinerated (with energy recovery). End-of-life modelling represents the situation in Northern Italy (67% curbside collection, 33% street containers).				
Indicators	**Climate change**	🟩				🟥
	Ozone depletion	🟨				🟥
	Photochemical ozone formation	🟥	🟥	🟥	🟨	🟩
	Acidification	🟥	🟥	🟥	🟨	🟩
	Terrestrial eutrophication	🟥	🟥	🟥	🟨	🟩
	Freshwater eutrophication	🟥	🟥	🟥	🟨	🟩
	Marine eutrophication	🟥	🟥	🟥	🟨	🟩
	Freshwater ecotoxicity	🟥	🟥	🟥	🟨	🟩
	Human toxicity (cancer effects)	🟥	🟥	🟥	🟨	🟩
	Human toxicity (noncancer effects)	🟥	🟥	🟥	🟨	🟩
	Particulate matter	🟥	🟥	🟥	🟨	🟩
	Water resource depletion	🟥	🟥	🟥	🟨	🟩
	Mineral and fossil resource depletion	🟥	🟥	🟥	🟨	🟩
	Cumulative energy demand	🟥	🟥	🟥	🟨	🟩

APPENDIX B

Table B35: Continued – Summary table: Dolci *et al*. (2016)- Breakfast cereal

	Products considered in study: BREAKFAST CEREAL				
	Traditional distribution (bag-in-box single-use packaging)				Loose distribution
	300 g	375 g	500 g	960 g	
Method	Characterization methods recommended by the Joint Research Centre of the European Commission, other than for mineral and fossil resource depletion which is on the basis of the "ultimate reserves" of resources. Cumulative energy demand was also calculated.				
Data and software	Ecoinvent database and SimaPro software				
Reviewed	Peer-reviewed journal article				

Table B36: Summary table: Dolci *et al*. (2016)- Rice

		Products considered in study: RICE			
		Best-performing single-use packaging: 1 kg bag	Loose distribution (self-dispensing system)		
			2 kg bag	5 kg bag	25 kg sack
Study scope	**Materials**	mixed plastic bag; corrugated cardboard box transport packaging	LDPE bag; LDPE heat-shrink film as transport packaging; Consumers purchase product in LDPE bag	LDPE bag; LDPE heat-shrink film as transport packaging; Consumers purchase product in LDPE bag	25 kg raffia sack; Consumers purchase product in LDPE bag
	Functional unit (FU)	The distribution of 1 kg of rice			
	Geographic region	Italy			
	Life cycle stages	Full life cycle of all packaging, packaging operations and transport to retail	Full life cycle of all packaging (cradle to grave), packaging operations, transport to retail, and full life cycle (cradle to grave) of the gravity bin dispenser		
	Use phase assumptions	n/a	Dispensers filled 3 times a week		
	End of life assumptions	All primary packaging separately collected, sorted and recycled, other than cellulose bags which are incinerated (with energy recovery). End-of-life modelling represents the situation in Northern Italy (67% curbside collection, 33% street containers).			
Indicators	**Climate change**	🟥	🟩	🟩	🟩
	Ozone depletion	🟨	🟥	🟨	🟩
	Photochemical ozone formation	🟥	🟩	🟩	🟩
	Acidification	🟥	🟨	🟩	🟩
	Terrestrial eutrophication	🟥	🟨	🟩	🟩
	Freshwater eutrophication	🟥	🟨	🟩	🟩
	Marine eutrophication	🟥	🟩	🟩	🟩
	Freshwater ecotoxicity	🟥	🟩	🟩	🟩
	Human toxicity (cancer effects)	🟥	🟨	🟩	🟩
	Human toxicity (noncancer effects)	🟥	🟨	🟩	🟩
	Particulate matter	🟥	🟨	🟩	🟩
	Water resource depletion	🟥	🟨	🟩	🟩
	Mineral and fossil resource depletion	🟥	🟨	🟩	🟩
	Cumulative energy demand	🟥	🟨	🟩	🟩
Method	Characterization methods recommended by the Joint Research Centre of the European Commission, other than for mineral and fossil resource depletion which is on the basis of the “ultimate reserves” of resources. Cumulative energy demand was also calculated.				
Data and software	Ecoinvent database and SimaPro software				
Reviewed	Peer-reviewed journal article				

APPENDIX B

Analyzing the Packaging Strategy of Packaging-Free Supermarkets: Scharpenberg *et al*. (2021)

The goal of this study is to clarify the potential environmental advantages of packaging-free supermarkets. In so doing, the authors conduct a **comparative LCA of six products retailed at the German packaging-free supermarket Original Unverpackt (OU) relative to conventionally packaged products** sold in small organic food stores. The products assessed are chia seeds, fruit bears, noodles, tofu, dishwashing shower gel and detergent[30].

The first three products (chia seeds, fruit bears and noodles) are typical of the dry bulk goods most often dispensed at packaging-free supermarkets. Product is transported to the store in bulk bags and used to fill the in-store dispensers. Customers bring their own reusable containers to dispense product into. The dispensed product is compared to a conventionally packaged product, either an LDPE, PP or mixed plastic bag (depending on the product) (see Table B37).

The functional unit applied in the comparison is the quantity of packaging material needed to transport and provide one unit of the conventionally packaged product, and one unit of the "packaging-free" product in its typical container size. The system boundary thus includes all primary, secondary and transport packaging, as well as the transport of the packaged product to the store. The product itself is excluded. For both the bulk- and conventionally-packaged products, all packaging is assumed to be discarded after use (either recycled, incinerated or landfilled, in accordance with the prevailing practices for that material type in Germany). The packaging-free system also includes the cleaning of dispensers after every charge, as well as the customers' home cleaning of the reusable containers (with containers assumed to be washed after every use). The manufacture and disposal of the dispensers themselves are not included, as this was judged to add very little to impacts owing to the relatively long service life of the dispensers (conservatively estimated to be seven years). Food loss was also excluded as it was also deemed to be very low for dry goods retailed at small supermarkets.

Summary of results and conclusions

The **environmental benefits of the bulk refill dispenser system (as practiced in packaging-free supermarkets) over conventional packaging depends on the food product, as well as on the conventional packaging against which it is being compared.** Two of the three dispensed products (chia seeds and noodles) were found to have lower impacts on climate change than conventionally packaged products.

Key findings in the comparison of food products sold at a packaging-free supermarket versus those sold conventionally packaged in small organic supermarkets are as follows:

- **Chia seeds**–where the dispensed product replaces conventional packaging with a high cardboard component–shows lower environmental impacts for the packaging-free product across all eight environmental indicators considered.
- **Noodles** similarly show environmental preference for the packaging-free product, although the need to wash dispensers and containers leads to the packaging-free noodles having higher water depletion than conventionally packaged noodles.
- Dispensed **fruit bears** do not show the environmental advantages of the other products since the sticky fruit bears place additional requirements on the cleaning of the dispensers. Packaging-free fruit bears were thus found to only have lower agricultural land occupation than conventionally packaged fruit bears, with all other impacts higher than the conventionally packaged fruit bears. However, if renewable energy rather than the energy grid mix is assumed to be used in the washing of dispensers and containers, then the dispensed fruit bears also have lower climate change, ionizing radiation and fossil depletion impacts than the conventionally packaged fruit bears.
- For **the conventionally packaged products, the manufacture of the packaging materials is the main cause of environmental impacts** across all impact categories. Corrugated cardboard boxes, used in the transport of the primary packages, are responsible for a high share of packaging manufacture impacts. Packaging disposal also makes a notable contribution to climate change and human toxicity impacts.
- **For the products sold in packaging-free supermarkets, manufacture of packaging, transport to store, and washing of dispensers and reusable containers are all important contributors to the environmental impacts.** In the washing of dispensers and containers, it is the use of energy that is the main cause of the high impacts from these processes.

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[30] Only the four food products are covered in this summary, given the focus of this report is on food packaging.

Table B37: Summary table: Scharpenberg *et al*. (2021)

		Products considered in study					
		Chia seeds		Fruit bears		Noodles	
		“packaging-free” (dispenser)	Conventionally packaged	“packaging-free” (dispenser)	Conventionally packaged	“packaging-free” (dispenser)	Conventionally packaged
Study scope	**Materials**	25 kg brown paper bag	LDPE/PP bag	2.5 kg PP bag	PP bag	5 kg LDPE bag	PP bag
	Functional unit (FU)	The quantity of packaging material needed to transport and provide one unit of the conventionally packaged counterpart of the “packaging-free” product in its typical container size.					
	Number per FU	210 g dispensed	1 x 210 g pack	100 g dispensed	1 x 100 g pack	500 g dispensed	1 x 500 g pack
	Weight	1.9 g brown paper; 1.81 g LDPE bubble wrap; 7.39 g corrugated cardboard	2.56 g LDPE/ PP; 15.65 g cardboard; 25.4 g corrugated cardboard; 0.12 g LDPE stretch film	0.56 g PP; 3.8 g corrugated cardboard	2.15 g PP; 7.85 g corrugated cardboard	3.8 g LDPE; 4.17 g corrugated cardboard	7 g PP; 27,75 g corrugated cardboard
	Geographic region	Germany					
	Life cycle stages	Cradle-to-grave, including the raw materials and production of all packaging (primary, secondary and tertiary), transport of packaging, use phase (washing and transport of reusable containers)					
	Use phase assumptions	Water, energy and detergent used in washing reusable containers (brought by customers) and cleaning dispensers are included. Reusable containers are assumed to be washed after every use, either by hand (59%) or in a dishwasher (41%). The product dispensers are cleaned after every charge either manually or in a dishwasher (depending on the product dispensed, e.g. fruit bear dispensers require more cleaning than noodle dispensers).					
	End of life assumptions	The shares of packaging materials incinerated, recycled or landfilled are according to German packaging ordinances. Recycled material substitutes raw material, with recycled material generally allocated by 50%. No energy credits are given.					
Indicators	**Agricultural land occupation**	🟩	🟥	🟩	🟥	🟩	🟥
	Urban land occupation	🟩	🟥	🟥	🟩	🟩	🟥
	Fossil depletion	🟩	🟥	🟥	🟩	🟩	🟥
	Ionizing radiation	🟩	🟥	🟥	🟩	🟥	🟩
	Resource depletion	🟩	🟥	🟥	🟩	🟩	🟥
	Human toxicity	🟩	🟥	🟥	🟩	🟩	🟥
	Climate change	🟩	🟥	🟥	🟩	🟩	🟥
	Water depletion	🟩	🟥	🟥	🟩	🟥	🟩
Method		ReCiPe Midpoint (Hierarchist) without long term.					
Data and software		Umberto NXT software and Ecoinvent v. 3.1 database					
Reviewed		Peer-reviewed journal article					

B.4 BIO-BASED PLASTICS (FOOD PRODUCT NOT EXPLICIT)

Environmental performance of bioplastic packaging on fresh food produce: A consequential life cycle assessment: Bishop, Styles and Lens (2021)

The aim of this study was to assess the environmental sustainability of substituting fossil fuel-derived food packaging with bio-based and biodegradable PLA packaging. This substitution was studied using consequential LCA, taking into account the opportunity for co-disposal of food and packing waste that arises with a switch to PLA packaging. The product system assumed that the current United Kingdom fossil fuel-based packaging market (19% PP, 19% LDPE, 31% HDPE and 31% PET) was substituted with PLA, with both packaging options treated using forward-looking end-of-life scenarios. These scenarios were based on European Commission regulations that are phasing out landfill disposal and prioritize industrial composting and anaerobic digestion of organic waste. As such, the end-of-life scenarios considered a mix of incineration, composting (home composting and industrial composting), anaerobic digestion, recycling and the production of insect feed from organic matter.

The functional unit was the management of 1 tonne of fresh fruit and vegetable food waste generated from households, which included 51.12 kg of food packaging. The consequential LCA system boundaries covered cradle-to-grave impacts and therefore included raw material extraction/production, plastic production and end-of-life management of the food and packaging waste in the UK. Production formation (i.e. packaging formation) and the use phase were excluded due to the wide variability of potential applications and as they were assumed equivalent between the two product systems. It was also assumed that food losses did not vary between the two product systems and no upstream food production impacts were considered. All modelling and impact assessment was conducted in OpenLCA 1.10.2 using the Environmental Footprint 2.0 (EF 2.0) impact assessment methodology. Impacts were therefore reported against 16 impact categories: acidification – terrestrial and freshwater; human health effects – cancer; eutrophication – freshwater; eutrophication – terrestrial; climate change; ecotoxicity – freshwater; ecotoxicity – marine; ionising radiation; land use; human health effects – non-cancer; resource use – energy carriers; resource use – minerals and metals; ozone depletion; photochemical ozone formation; respiratory inorganics; and water scarcity.

The key study parameters and results are summarized in Table B38.

Summary of results and conclusions

The **use of PLA packaging results in impacts greater than fossil fuel-based packaging in most impact categories when “standard” end-of-life management options are applied** (particularly scenario 1). Across all scenarios, plastic production and end-of-life management of the food waste result in the greatest impacts for most impact categories. As such, the diversion of more waste to anaerobic digestion results in improved impacts for the PLA packaging. Scenario 4, where 70% of waste is anaerobically digested and only 5% is incinerated, has better impacts than the fossil fuel-based scenario for 6 of the 16 impact categories, **while if 100% of the waste is sent to anaerobic digestion, the PLA has better environmental performance in half the impact categories**.

Of the PLA scenarios, the production of insect feed has the lowest environmental impacts, as the insect feed is used to replace fishmeal and soybean meal. The avoided emissions result in this scenario having better environmental performance than fossil fuel-based packaging in 11 of the 16 impact categories. In all PLA scenarios, the acidification, marine eutrophication, terrestrial eutrophication, ozone depletion and water scarcity impacts are increased. These increases are due to the cultivation of maize feedstock for PLA production.

Table B38: Summary table: Bishop, Styles and Lens (2021)

		Products considered in study								
		Fossil fuel-based packaging	PLA – S1	PLA – S2	PLA – S3	PLA – S4	PLA–AD	PLA–Composting	PLA–Incineration	PLA – Insect feed
Study scope	**Functional unit (FU)**	1,000 kg of fresh fruit and vegetable waste, including packaging								
	Weight [kg]	51.12 kg packaging								
	Geographic region	UK								
	Life cycle stages	Cradle-to-grave excluding plastic product formation and use stages, as well as upstream food production								
	Use phase assumptions	Use phase not considered								
	End-of-life assumptions	15% home composting (HC) 10% industrial composting (IC) 10% anaerobic digestion (AD) 65% incineration (I)	15% HC 10% IC 10% AD 65% I	10% HC 10% IC 30% AD 45% I	10% HC 10% IC 50% AD 25% I	10% HC 10% IC 70% AD 5% I	100% AD	100% IC	100% I	100% insect feed production
Indicators	**Acidification – terrestrial and freshwater**	🟩	🟨	🟨	🟨	🟨	🟨	🟥	🟨	🟨
	Human health effect–Cancer	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟩
	Eutrophication–Freshwater	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟩
	Eutrophication–Terrestrial	🟩	🟨	🟨	🟨	🟨	🟨	🟥	🟩	🟥
	Climate change	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟨	🟩
	Ecotoxicity–Freshwater	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟩
	Eutrophication–Marine	🟩	🟨	🟨	🟨	🟨	🟨	🟥	🟨	🟩
	Ionising radiation	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩
	Land use	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩
	Human health effects – Non-cancer	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟩
	Resource use – Energy carriers	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟩
	Resource use – Minerals and metals	🟨	🟥	🟨	🟨	🟨	🟨	🟥	🟥	🟩
	Ozone depletion	🟩	🟥	🟨	🟨	🟨	🟨	🟥	🟥	🟩
	Photochemical ozone formation	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟩
	Respiratory inorganics	🟨	🟨	🟨	🟨	🟨	🟩	🟥	🟨	🟨
	Water scarcity	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Method	Environmental Footprint 2.0									
Data and software	OpenLCA, using ecoinvent 3.5									
Reviewed	Peer reviewed journal article									

Twisting biomaterials around your little finger: environmental impacts of bio-based wrappings: Hermann, Blok and Patel (2010)[31]

The aim of this study was to assess the environmental sustainability of bio-based printed packaging films in comparison to conventional, fossil fuel-based printed packaging films used for snack packaging. Whilst all the bio-based wrappings considered in the study are made using biomaterials not all are biodegradable, e.g. PLA, cellulose and bio-based polyester (BBP) are biodegradable, whilst Bio-PE is not. The study compares cradle-to-grave environmental impacts of film snack packages manufactured from the 29 film combinations listed in Table B39. The Oriented polypropylene (OPP) / Polyethylene (PE) / Metallized OPP (MOPP) films and PE or OPP films are considered the conventional film materials (highlighted in light grey in Packaging film options included in Hermann, Blok and Patel (2010) study. Film materials highlighted in grey used for the baseline comparison.) and so used for the baseline comparison.

Table B39: Packaging film options included in Hermann, Blok and Patel (2010) study. Film materials highlighted in grey used for the baseline comparison.

Inner pack material (i.e. contact with food and serve as water and oxygen barriers)	Outer pack materials (i.e. no contact with food and no barrier requirements)
1a. Oriented polypropylene (OPP) / Polyethylene (PE) / Metallized OPP (MOPP)	**5a.** PE
1b. OPP / PE / MOPP [thicker film]	**5b**. Bio-based PE [thicker film]
2a. Paper / PE / MOPP	**5c.** Bio-based PE
2b. Cellulose / PE / MOPP	**6.** OPP
2c. Polylactic acid (PLA) / PE / MOPP	**7.** PLA
3a. Metallized PLA (MPLA) / PLA / PLA	**8a.** Cellulose
3b. PLA / AlOx coated PLA	**8b.** Cellulose [thicker film]
3c. PLA / SiOx coated PLA	**9a**. Paper / OPP
3d. SiOx coated PLA / SiOx coated PLA	**9b.** Paper / PLA
3e. MPLA / MPLA	**9c.** Paper / PLA [thicker film]
4a. Paper / SiOx coated PLA / PLA	**9d.** Paper PE
4b. Paper / Aluminium / PLA	**9e**. Paper / Bio-based polyester [thicker film, with adhesive between layers]
4c. Paper / Metallized polyethylene terephthalate (MPET) / PP (peel removable)	**9f.** Paper / Bio-based polyester [adhesive between layers]
4d. Paper / MPET / PE (peel removable)	**9g.** Paper / Bio-based polyester [thinnest film, with no adhesive between layers]
	9h. Paper / Ethyl vinyl acetate (EVA)

The functional unit was 1 m^2 of packaging film. The study's system boundaries focused on cradle-to-grave impacts and therefore included raw material extraction/production; film manufacture, laminating and printing; film distribution; and film end-of-life (incineration, landfilling, composting and digestion). Film cutting, sealing and filling is excluded, as this is assumed equivalent across all scenarios. Impact assessment results are reported at both the cradle-to-gate and cradle-to-grave level. In order to allow this reporting, biogenic carbon sequestered in bio-based plastics is accounted for in both the plastic product and during end-of-life management. Impact assessment was calculated using the CML baseline 2000 mid-point method, with water use and land use impact categories added.

The key study parameters and results are summarized in Table B40 for inner packs (films that are in contact with food and serve as oxygen and water barriers) and Table B41 for outer packs (films that are not in contact with food and have no barrier requirements).

Summary of results and conclusions

Films manufactured fully or partly from bio-based materials can have the same or lower impacts than traditional fossil fuel-derived films; however, numerous bio-based

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[31] This study is included in the meta-analysis even though it does not fully meet the selection criteria (it is from 2010) because few studies looking at snack packaging were found in the literature.

and biodegradable plastic film options have significantly increased impacts compared to the reference films.

For inner packs, the traditional OPP film, as well as laminated Paper / OPP film, have the lowest cradle-to-gate impacts and cradle-to-grave global warming potential. In terms of outer packs, bio-PE, Paper / EVA and Paper / BBP films have the lowest impacts and perform better than traditional OPP or PE films. It should also be noted that current technology for production and processing of bio-based films is less established than that used for traditional fossil fuel-derived films and therefore less efficient. This increases the impacts associated with bio-based films, although these differences are likely to be reduced as the associated technologies mature. Other findings are summarized below:

- **Inner packs**
  - Traditional OPP film (reference film) has amongst the best impacts for global warming potential, total energy use, photochemical oxidant formation, acidification, eutrophication, water use and land use.
  - Paper / OPP film has better impacts than the OPP film for non-renewable energy use, global warming potential and abiotic depletion potential, along with equivalent impacts for total energy use, photochemical oxidant formation and acidification. However, it has worse eutrophication, water use and land use impacts.
  - PLA film made with renewable energy has amongst the best non-renewable energy use, global warming potential and abiotic depletion potential impacts; however, in other categories it has higher impacts than the OPP film.
- **Outer packs**
  - Traditional OPP film (one of two reference films) has amongst the best impacts for total energy use, eutrophication, water use and land use, and better performance than traditional PE film (the other reference film) in all categories.
  - Thin bio-PE film has improved impacts when compared with the OPP film for all categories except acidification and eutrophication.
  - Bio-based polyesters have improved impacts when compared with the OPP film for non-renewable energy use, global warming potential and abiotic depletion potential; however, in other categories they perform equivalently or considerably worse (total energy use, eutrophication, water use and land use).
  - Landfilled bio-PE and Paper / EVA films have the lowest global warming potential.

APPENDIX B

Table B40: Summary table: Hermann, Blok and Patel (2010) – Inner packs

			Inner packs considered in study														
			1a	1b	2a	2b	2c	3a	3b	3bw	3c	3d	3e	4a	4b	4c	4d
Study scope	**Materials**		OPP/PE/MOPP	OPP/PE/MOPP	Paper/PE/MOPP	Cellulose/PE/MOPP	PLA/PE/MOPP	MPLA/PLA/PLA	PLA/AlOx coated PLA	PLA/AlOx coated PLA (with wind credits)	PLA/SiOx coated PLA	PLA SiOx coated/SiOx coated PLA	MPLA/MPLA	Paper/SiOx coated PLA/PLA	Paper/Aluminium/PLA	Paper/MPET/Peelable PP	Paper/MPET/Peelable PE
	Functional unit (FU)		1 m³ of film														
	Weight [g]		39	48	51	54	51	63	53	53	52	52	52	86	74	77	75
	Geographic region		Europe														
	Life cycle stages		Cradle-to-grave and cradle-to-factory gate														
	Use phase assumptions		Film cutting, filling and sealing assumed consistent and therefore excluded														
	End-of-life assumptions		Incineration with energy recovery; landfilling with landfill gas recovery; composting (where applicable); and anaerobic digestion (where applicable) all considered separately.														
Indicators – Cradle-to-gate	**Non-renewable energy use**		🟨	🟨	🟩	🟨	🟨	🟨	🟨	🟩	🟨	🟨	🟨	🟥	🟥	🟨	🟨
	Total energy use		🟩	🟨	🟩	🟨	🟥	🟥	🟨	🟨	🟨	🟥	🟨	🟥	🟥	🟨	🟨
	Global warming potential		🟨	🟨	🟩	🟨	🟨	🟨	🟥	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨
	Abiotic depletion potential		🟨	🟨	🟩	🟨	🟨	🟨	🟨	🟩	🟨	🟨	🟨	🟥	🟥	🟨	🟨
	Photochemical oxidant formation		🟩	🟨	🟩	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟨
	Acidification potential		🟩	🟨	🟩	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	Eutrophication potential		🟩	🟨	🟨	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	Water use		🟩	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟥	🟨	🟥	🟥	🟨	🟨
	Land use		🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨
Indicators – Cradle-to-grave	**Global warming potential**	**Incineration with energy recovery**	🟩	🟨	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟨	🟨
		Landfill with gas recovery	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟨	🟨
		Composting						🟥	🟨	🟩	🟨	🟥	🟨	🟥			
		Digestion						🟥	🟨	🟩	🟨	🟥	🟨	🟥			
Method	CML 2 baseline 2000, with water use (process, cooling and irrigation water use only) and land use (agricultural and forestry land use only)																
Data and software	SimaPro, using ecoinvent and primary data collected from companies																
Reviewed	Peer reviewed journal article																

Table B41: Summary table: Hermann, Blok and Patel (2010) – Outer packs

			Outer packs considered in study															
			5a	5b	5c	6	7	7w	8a	8b	9a	9b	9c	9d	9e	9f	9g	9h
Study scope	**Materials**		PE	Bio-PE	Bio-PE	OPP	PLA	PLA (with wind credits)	Cellulose	Cellulose	Paper/OPP	Paper/PLA	Paper/PLA	Paper/PE	Paper/Bio-based polymer	Paper/Bio-based polymer	Paper/Bio-based polymer	Paper/EVA
	Functional unit (FU)		1 m^3 of film															
	Weight [g]		61	61	33	29	37	37	28	43	41	53	68	55	85	70	51	40
	Geographic region		Europe															
	Life cycle stages		Cradle-to-grave and cradle-to-factory gate															
	Use phase assumptions		Film cutting, filling and sealing assumed consistent and therefore excluded															
	End-of-life assumptions		Incineration with energy recovery; landfilling with landfill gas recovery; composting (where applicable); and anaerobic digestion (where applicable) all considered separately.															
Indicators – Cradle-to-gate	**Non-renewable energy use**		🟥	🟨	🟩	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩
	Total energy use		🟨	🟨	🟨	🟩	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟥
	Global warming potential		🟨	🟩	🟩	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	Abiotic depletion potential		🟨	🟨	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟨	🟩
	Photochemical oxidant formation		🟨	🟨	🟨	🟨	🟥	🟥	🟨	🟥	🟩	🟨	🟥	🟩	🟨	🟨	🟨	🟩
	Acidification potential		🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟥	🟥	🟨	🟨	🟨	🟩
	Eutrophication potential		🟨	🟥	🟥	🟩	🟨	🟨	🟥	🟥	🟩	🟨	🟨	🟨	🟥	🟥	🟥	🟩
	Water use		🟩	🟨	🟩	🟩	🟨	🟩	🟨	🟥	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨
	Land use		🟩	🟥	🟨	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨
Indicators – Cradle-to-grave	**Global warming potential**	**Incineration with energy recovery**	🟨	🟨	🟩	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩
		Landfill with gas recovery	🟨	🟩	🟩	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
		Composting					🟨	🟩	🟨	🟥		🟨	🟨		🟩	🟩	🟩	
		Digestion					🟨	🟩	🟨	🟥		🟨	🟨		🟩	🟩	🟩	
Method	CML 2 baseline 2000, with water use (process, cooling and irrigation water use only) and land use (agricultural and forestry land use only)																	
Data and software	SimaPro, using ecoinvent and primary data collected from companies																	
Reviewed	Peer reviewed journal article																	

APPENDIX B

Biopolymer production and end of life comparisons utilising life cycle assessment: Hottle, Bilec and Landis (2017)

The aim of this paper was to assess the environmental sustainability of bio-based plastics in comparison to traditional, fossil fuel-derived plastics, while also considering end-of-life disposal methods. This is in recognition of the fact that not all bio-based plastics are biodegradable, and that end-of-life disposal methods affect the environmental performance of plastic options (both biodegradable and non-biodegradable). Even though end-of-life disposal of plastics is of growing concern, it has largely, up until now, been ignored in LCA studies. Certain bio-based plastics, such as PLA and TPS, are biodegradable and therefore allow for composting as an alternative end-of-life disposal method. The comparative cradle-to-grave LCA compares the following eight polymers,

- Polylactic acid (PLA), produced from corn using the Ingeo process
- Thermoplastic starch (TPS), produced from corn
- Polyethylene terephthalate (PET)
- Bio-PET, produced from bio-ethylene glycol produced from sugar cane (i.e. terephthalic acid is still fossil fuel-based)
- High density polyethylene (HDPE)
- Bio-HDPE, produced from bio-ethylene produced from sugar cane
- Low density polyethylene (LDPE)
- Bio-LDPE, produced from bio-ethylene produced from sugar cane

Two disposal methods are considered for each polymer; landfilling or composting for the bio-based and biodegradable polymers (PLA and TPS), and landfilling or recycling for non-biodegradable polymers, i.e. 16 scenarios are explored in total.

The functional unit is one kilogram of plastic. The study's system boundaries cover cradle-to-grave emissions and therefore include raw material extraction/production, plastic production and end-of-life management in the USA. Product formation (e.g. bottle blowing, thermoforming) and use are excluded due to the wide variability of potential applications for the polymers considered. Impact assessment was conducted with TRACI 2.1.

The key study parameters and results are summarized in Table B42.

Summary of results and conclusions

The production of bio-based plastics results in impacts greater than fossil fuel-derived plastics in most impact categories, with the exception of global warming and fossil fuel depletion impacts. However, considering only production does not provide a full sense of the life cycle impacts of plastic use, as all end-of-life options have associated, and often significant, life cycle environmental impacts. **Recycling is the best end-of-life option when offset credits are attributed to the plastic.** When considering the overall life cycle, **bio-based plastics perform better in certain impact categories, while traditional, fossil fuel-derived plastics perform better in other categories**, particularly those linked to human health. Other findings are summarized below:

- **Production**
  - Bio-ethylene derived (non-biodegradable) plastics (bio-PET, bio-LDPE and bio-HDPE) have the greatest impacts across all impact categories except global warming and fossil fuel depletion, as agricultural production of sugar cane and downstream processing (ethanol and ethylene production) are significant impact sources.
  - Corn-derived bio-based and biodegradable plastics (PLA and TPS) have greater acidification and eutrophication impacts than fossil fuel-derived plastics, as agricultural production of corn, as well as wastewater production during starch production, are key impact sources.
  - Bio-based plastics (both biodegradable and non-biodegradable) have lower global warming and fossil fuel depletion impacts than equivalent fossil-fuel derived plastics.
- **End-of-life**
  - Impacts from landfilling of non-biodegradable plastics are relatively minor, since polymers do not degrade. Global warming impacts are significant for bio-based and biodegradable polymers (PLA and TPS), while TPS also has high eutrophication impacts associated with landfilling.
  - Impacts from composting of PLA and TPS are greater than landfilling impacts for smog formation, acidification, carcinogens, non-carcinogens, respiratory effects and ecotoxicity; however, they are lower than the impact from landfilling for ozone depletion, global warming and eutrophication.
  - Impacts from recycling are less than landfilling impacts for global warming, eutrophication, carcinogens, non-carcinogens, ecotoxicity and fossil fuel depletion. However, they are greater than landfilling impacts for ozone depletion, smog formation and in the case of PE, acidification and respiratory effects. Impacts from recycling operations are primarily due to the transport of material to overseas recyclers and in the case of respiratory effects, from the recycling process itself.
  - Attributing offset recycling credits lowers the global warming and fossil fuel depletion impacts to below the impacts associated with production. For PET, offset credits also lower carcinogens, non-carcinogens, respiratory effects and ecotoxicity impacts to below production impacts.

Table B42: Summary table: Hottle, Bilec and Landis (2017)

		Products considered in study															
		PLA	TPS	PET	Bio-PET	HDPE	Bio-HDPE	LDPE	Bio-LDPE	PLA	TPS	PET	Bio-PET	HDPE	Bio-HDPE	LDPE	Bio-LDPE
Study scope	**Functional unit (FU)**	1 kg of polymer															
	Weight [kg]	1 kg															
	Geographic region	USA (where appropriate, underlying datasets were adapted to better represent USA)															
	Life cycle stages	Cradle-to-grave excluding plastic product formation and use stages															
	Use phase assumptions	Use phase not considered															
	End-of-life assumptions	Landfilled – In the case of PLA where there is considerable uncertainty in landfill degradability, two scenarios were modelled.								Composted		Recycled – Benefits of offsetting virgin material production are allocated to the recycled plastics.					
Indicators	**Ozone depletion**	🟩	🟥	🟨	🟨	🟩	🟨	🟨	🟨	🟩	🟥	🟨	🟨	🟨	🟨	🟨	🟨
	Global warming	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟨	🟩
	Smog	🟨	🟩	🟨	🟨	🟩	🟨	🟩	🟨	🟨	🟩	🟨	🟨	🟨	🟥	🟨	🟥
	Acidification	🟥	🟥	🟨	🟥	🟩	🟨	🟩	🟨	🟥	🟥	🟨	🟨	🟨	🟨	🟩	🟥
	Eutrophication	🟨	🟥	🟨	🟨	🟨	🟨	🟩	🟨	🟨	🟥	🟨	🟨	🟩	🟨	🟩	🟨
	Carcinogenics	🟩	🟨	🟥	🟥	🟨	🟨	🟨	🟨	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	Non-carcinogenics	🟩	🟩	🟨	🟨	🟩	🟥	🟩	🟥	🟩	🟩	🟩	🟨	🟩	🟥	🟩	🟥
	Respiratory effects	🟩	🟨	🟨	🟨	🟩	🟥	🟩	🟥	🟩	🟨	🟨	🟨	🟨	🟥	🟨	🟥
	Ecotoxicity	🟩	🟨	🟨	🟨	🟨	🟥	🟨	🟥	🟩	🟨	🟨	🟨	🟨	🟥	🟨	🟥
	Fossil fuel depletion	🟨	🟨	🟨	🟨	🟥	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟨	🟩
Method	TRACI 2.1 mid-point																
Data and software	ecoinvent v 2 and v 3, US LCI v 1.6 (including Franklin & Associates reports), literature data and primary data from site visits																
Reviewed	Peer reviewed journal article																

Life cycle assessment of single use thermoform boxes made from polystyrene (PS), polylactic acid (PLA), and PLA/starch–Cradle to consumer gate: Suwanmanee *et al.* (2012)[32]

The aim of this study was to assess the environmental sustainability of bio-based and biodegradable plastics options to replace thermoformed PS boxes in Thailand. As such, the study compares cradle-to-gate environmental impacts of thermoformed boxes manufactured from two bio-based and biodegradable plastics, namely PLA (corn derived, utilising the Ingeo process) and a PLA/starch blend (corn derived PLA and cassava derived starch), to traditional thermoform boxes manufactured from fossil fuel-derived PS. In all cases, the packaging is manufactured using cast sheet extrusion, followed by thermoforming. The impact of Thailand's grid electricity mix was also investigated with scenarios considering production using electricity produced from coal (traditional generation and integrated gasification combined cycle generation) and

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[32] This study is included in the meta-analysis even though it does not fully meet the selection criteria (it does not cover the full life cycle) because relatively few studies from developing countries were found in the literature.

natural gas.

The functional unit was 10,000 thermoform boxes with a carrying capacity of 100 g (10 x 8 x 2.5 cm). The study only focused on cradle-to-consumer gate impacts. As such, the system boundary includes raw material extraction, plastic production, thermoformed box manufacture and distribution of the boxes to consumers within Thailand. End-of-life is excluded. All impacts were reported against three impact categories: global warming potential (direct GHG emissions and indirect land use change (LUC) emissions), acidification and photochemical ozone formation, as these were considered the most important impacts linked to production.

The key study parameters and results are summarized in Table B43.

Summary of results and conclusions

Across all impact categories and scenarios, **fossil fuel-derived PS has the lowest impacts.** This is due to the high impacts of corn and cassava production and energy consumption in the Ingeo PLA production process. **Land use changes are the key source of climate change impacts for both PLA products**, accounting for between 82% and 91% of total GWP. However, even if LUC global warming impacts are excluded, PS boxes have the lowest GWP.

Scenario analysis around the generation of electricity used for thermoform box production shows that utilising cleaner electricity generation methods (natural gas or integrated gasification combined cycle coal generation) reduces overall impacts. Cleaner electricity generation brings the impacts of the two PLA-based boxes closer to those of the PS box; however, the PS box still has lower impacts across all three impact categories.

Table B43: Summary table: Suwanmanee *et al*. (2012)

		Products considered in study		
		PS	**PLA**	**PLA/starch blend**
Study scope	**Materials**	Polystyrene produced from petroleum	Polylactic acid produced from corn	70% PLA produced from corn 30% starch produced from cassava
	Functional unit (FU)	10,000 thermoformed trays (10 x 8 x 2.cm with carrying capacity of 100 g)		
	Weight [kg]	447.60	597.60	549.56
	Geographic region	Manufactured in Thailand		
	Life cycle stages	Cradle-to-consumer gate (not including production of packaged product, filling, sealing, use or end-of-life)		
	End-of-life assumptions	End-of-life not included		
Indicators	**Global warming potential excl. LUC**	🟩	🟨	🟥
	Global warming potential incl. LUC	🟩	🟥	🟨
	Acidification	🟩	🟥	🟨
	Photochemical ozone formation	🟩	🟥	🟨
Method	EDIP 2003			
Data and software	ecoinvent v 1.01 and v 2.2, in combination with the Thailand energy database			
Reviewed	Peer reviewed journal article			

Appendix C: **Case studies integrating marine litter impacts into existing LCA impact categories**

This appendix provides the summarized results of three LCA case studies of a new impact category assessing potential physical impacts caused when organisms ingest microplastics (*physical effects on biota*). Full details and further discussion on the limitations can be found in Corella-Puertas *et al*. (2022) and Corella-Puertas and Boulay (in preparation).

For the three case studies, the inventory of plastic emissions was based on the Plastic Leak Project guidelines (Plastic Leak Project 2020). Plastic emissions include leakage of plastic pellets (primary microplastics) at the pre-production stage and leakage of macroplastics at the end-of-life. There are still significant limitations on the inventory side for modelling marine plastic impacts. For example, for plastic pellet losses in the pre-production of plastic, the uncertainty is beyond one order of magnitude (Plastic Leak Project 2020). Waste import/export is also not taken into account. Macroplastic leakage and fragmentation rates (production of secondary microplastics) are based on expert estimates. Further research is needed to improve these estimates.

Different fragmentation scenarios of macroplastics into secondary microplastics were tested (10%, 50%, and 100% fragmentation within 100 years). For the LCIA, preliminary *physical effects on biota* characterization factors were developed for different microplastics (EPS, PP, PLA, HDPE) at midpoint (problem) and endpoint (damage) levels. Since there is uncertainty regarding the fate of microplastics in the environment, different scenarios were proposed: best case, medium case, and worst case. The current characterization factors for physical effects on biota are therefore preliminary. Their goal is to test different best- to worst-case scenarios, as well as assess the importance of different fate mechanisms. Research is ongoing to refine the fate of microplastics in the environment, and will help to reduce the characterization factor uncertainty.

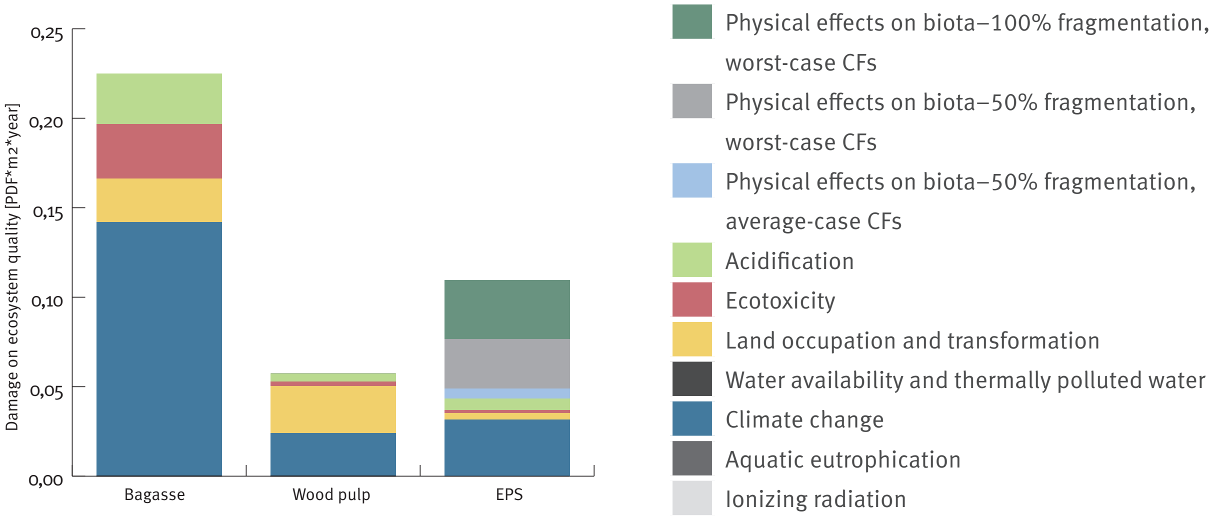
Single-use food trays for on-the-go meals (Corella-Puertas *et al*. 2022)

Corella *et al*. (2022) compared the potential impacts of single-use food trays to carry an on-the-go meal for one person in Montreal in 2021. Specifically, the study compared one plastic option (EPS) and two compostable alternatives (bagasse and wood pulp). Although the case study application was single-use food trays, the materials types assessed have strong overlap with those in fresh produce and meat packaging. For example, a PS tray and moulded pulp tray are amongst the option set included in Belley *et al* (2011) for the packaging of fruit and vegetables in Canada.

Overall, the bagasse tray shows the highest damage to ecosystem quality – climate change is the highest contributor (Figure C1). Without considering the potential impacts of marine plastic litter, EPS and wood pulp results are in the same range of magnitude. Once *physical effects on biota* from microplastic emissions are taken into account, the overall damage of EPS trays may change significantly, particularly for the worst-case scenarios. The high uncertainty of the *physical effects on biota* impacts is mainly linked with the uncertainty of the fate of microplastics in the environment (specifically of fragmentation, degradation and sedimentation rates).

APPENDIX C

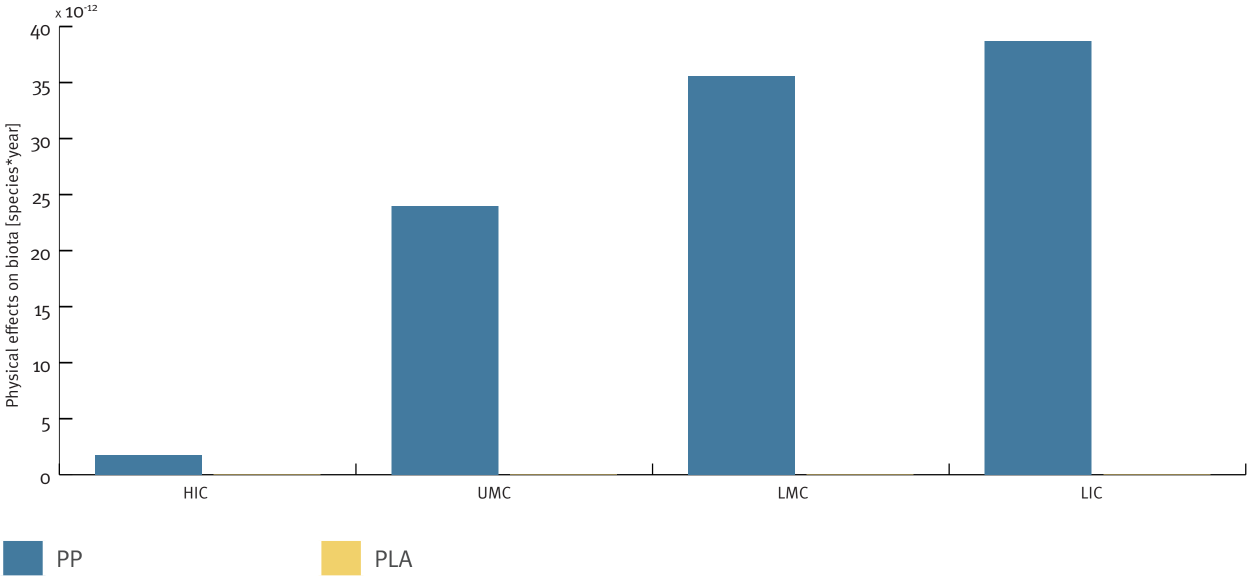
Figure C1: Potential impacts of different types of single-use food trays on ecosystem quality, shown by aggregated impact categories. For the impact category of *physical effects on biota*, results calculated with best-case scenario characterization factors (CFs) are not displayed here due to their small size. Adapted from Corella-Puertas *et al.* (2022)



Single-use bags for fresh-cut vegetables (Vigil *et al.* 2020)

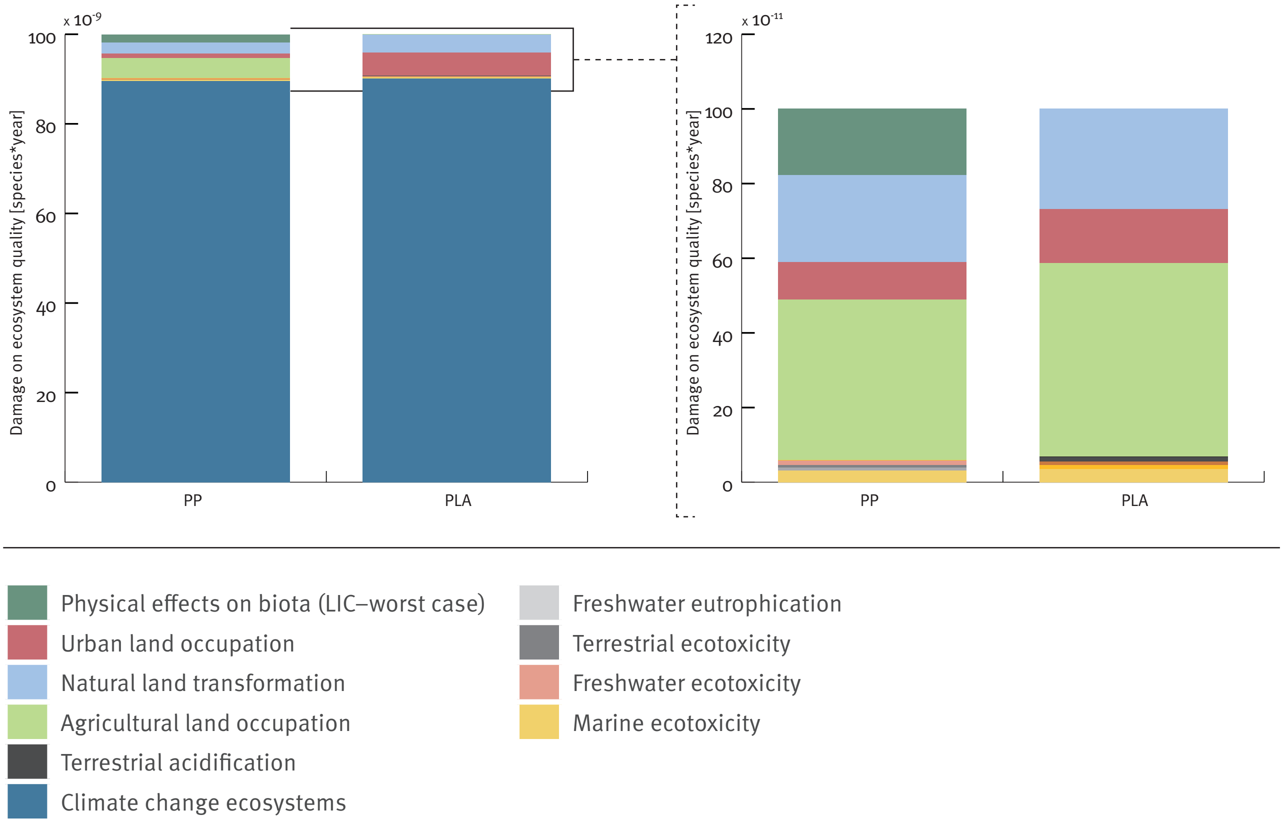
Vigil *et al*. (2020) compared the potential impacts of single-use bags containing 130 g of fresh-cut lettuce, used in Italy. The study compared bags of PP (reference), PP with ZnO particles, and PLA with ZnO particles. The authors provided endpoint results for the area of protection of ecosystem quality (not reported in the original manuscript), which they calculated with ReCiPe (personal communication, 2022). The new category of *physical effects on biota* impacts of microplastic emissions was added to the original results, as described above. This report does not include the results of PP reference bags and assumes that the *physical effects on biota* impacts of the two PP bags are similar (i.e. that the ZnO does not affect significantly the degradation, fragmentation or sedimentation rate). Furthermore, a regionalization study was carried out for *physical effects on biota*, considering that the use and end-of-life stages of lettuce bags occurred in different countries due to different littering and (formal and informal) waste management practices. Depending on the region, the potential marine litter impacts can vary up to two orders of magnitude (Figure C2). Despite the high uncertainty, PLA microplastics impacts seem to be significantly smaller than PP microplastics impacts (Corella-Puertas and Boulay no date). This is linked to the faster sedimentation rates of PLA. Both for PP and PLA, *physical effects on biota* impacts barely change the overall damage on ecosystem quality, even in the worst-case scenarios (Figure C3). Overall, climate change impacts have the largest contribution to the damage on ecosystem quality.

Figure C2: Damage of microplastic litter from lettuce bags to ecosystem quality (impact category: physical effects on biota) for different regionalization scenarios, calculated using worst-case characterisation factors with 100% fragmentation of macroplastic litter into microplastics within 100 years. It is assumed that the microplastics are film fragments with an initial thickness of 1000 µm. Best-case and medium-case scenarios can be found in Corella-Puertas *et al*. (in preparation). HIC: High-income countries. UMC: Upper-middle-income countries. LMC: Lower-middle-income countries. LIC: Low-income countries.



APPENDIX C

Figure C3: Potential impacts of different types of single-use lettuce bags on ecosystem quality on ecosystem quality, based on the results of Vigil *et al*. (2020). Left: Impact categories of Vigil *et al*. (2020) and *physical effects on biota* from this work (worst-case scenario of Figure C2). Right: Climate change impacts removed for illustration purposes.



Reusable crates for vegetable and fruit transportation (Abejón *et al*. 2020)

Abejón *et al*. (2020) compared the potential impacts of reusable plastic crates and cardboard boxes for fruit and vegetable transportation in Spain. The plastic crates were either made of PP or HDPE, but the inventory values were an average of the two (Abejón *et al*. 2020). The study presented midpoint-level impacts calculated with CML, which were taken to endpoint level with ReCiPe conversion factors (Corella-Puertas and Boulay no date). The new category of *physical effects on biota* impacts of microplastic emissions was added to the original results, as described above. Furthermore, a regionalization study was carried out for physical effects on biota, considering that the use and end-of-life stages of plastic crates occurred in different countries. Similar to the regionalization based on Vigil *et al*. (2020), the potential marine litter impacts can vary up to two orders of magnitude depending on the region (Figure C4). PP was found to have slightly lower potential impacts than HDPE, although this finding may not be significant given the high uncertainty of the results. For both polymers, physical effects on biota impacts are negligible compared to the overall damage on ecosystem quality, even in the worst-case scenarios (Figure C5). Similar to the results of Vigil *et al*. (2020), climate change impacts have the largest overall contribution to the damage on ecosystem quality.

Figure C4: Damage of microplastic litter to ecosystem quality per reusable plastic crate (impact category: physical effects on biota) for different regionalization scenarios, calculated using worst-case characterization factors and 100% fragmentation of macroplastic litter into microplastics within 100 years. Best-case and medium-case scenarios can be found in Corella-Puertas *et al*. (in preparation). It is assumed that the microplastics have a spherical shape with an initial diameter of 1000 µm. The original study of Abejón *et al*. (2020) was located in Spain only. HIC: High-income countries. UMC: Upper-middle-income countries. LMC: Lower-middle-income countries. LIC: Low-income countries.

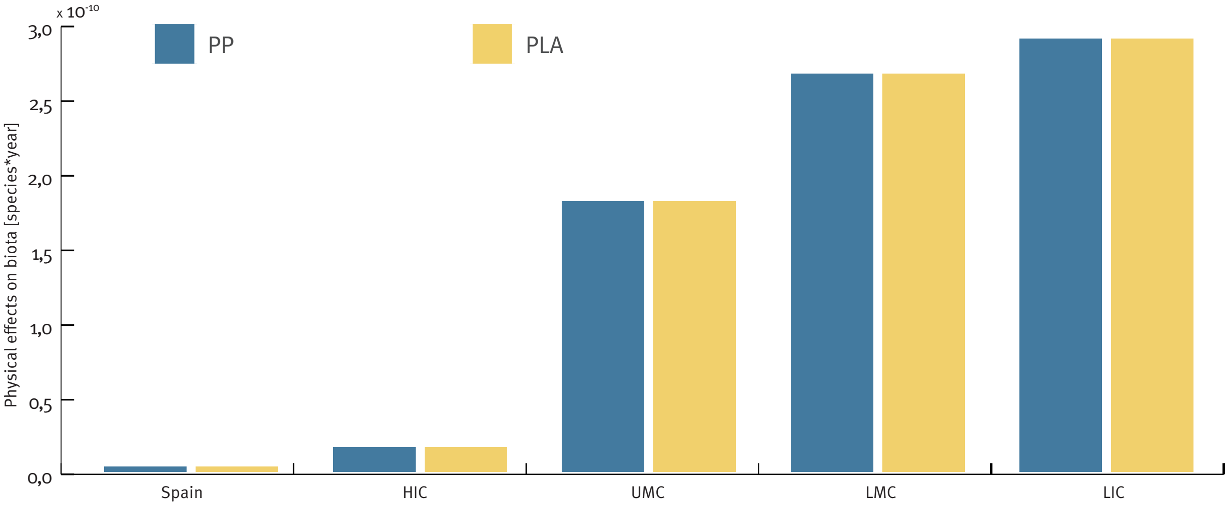
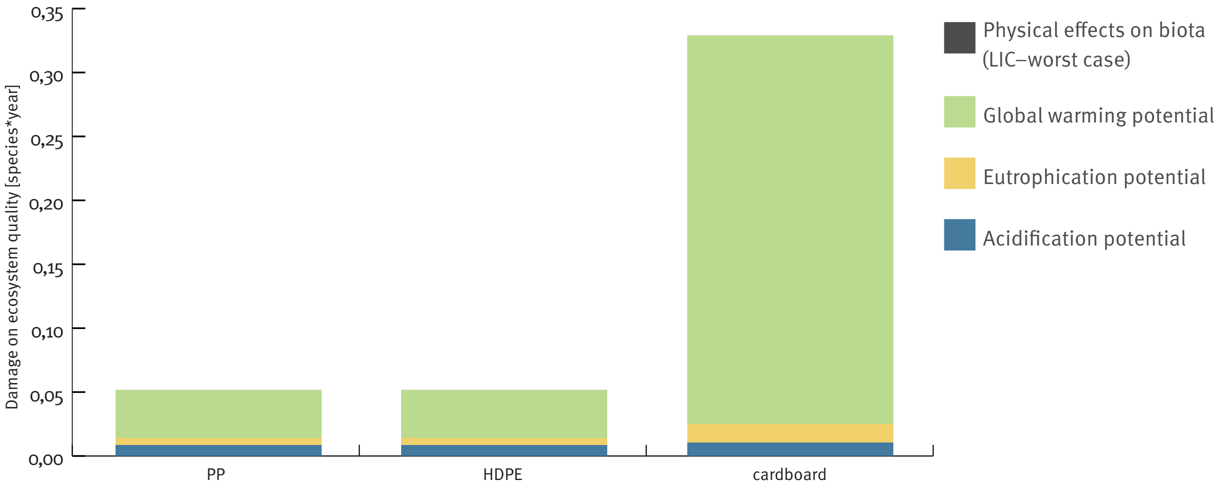


Figure C5: Potential impacts of different types of reusable crates on ecosystem quality, based on one of the two scenarios presented in Abejón *et al*. (2020) (conservative scenario). The impact category of physical effects on biota was added in this work, and corresponds to the worst-case scenario in Figure C4.



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