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TITLE: Environmental Impacts of Plastic Packaging of Food Products

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Abstract

Life cycle assessment (LCA) is used widely to compare the relative impacts of different packaging materials for a specific food product, but few studies evaluate how a single packaging material contributes to a variety of food items. Plastic is a common material used for food packaging. This study conducts an analysis of 28 studies that conduct an LCA of food products to quantify the impact of plastic packaging relative to the total life cycle impact of food products. For most of the 13 environmental indicators reported, plastic packaging is responsible for less than 10% of total life cycle emissions of 23 out of the 30 foods studied. Relative packaging emissions tend to be higher for liquids and food products packaged in small quantities, although the absolute values of energy use and greenhouse gas (GHG) emissions are small. To make LCA results more accessible to non-scientific audiences, this study compares the results to a reference value of the emissions of vehicle travel. The environmental impact caused by the packaging from per capita annual food consumption is less than the environmental impact of per capita daily vehicle travel for most food products analyzed, although annual beverage consumption can be responsible for the equivalent impact of 76 miles of driving.

Keywords

Life cycle assessment; Food packaging environmental impact; Plastic food packaging; Environment; Break-even analysis; Food system

Highlights

- Packaging is not a dominant environmental impact source for food product.
- Liquid food packaging generally has a higher impact contribution than solid food packaging.
- The most consumed food with high impact per functional unit (i.e., beverage) should be prioritized for sustainability improvements.

1. Introduction

Consumption of packaged foods has risen substantially in recent decades. With a 5% annual growth rate, the worldwide packaged food market was valued at \$1.9 trillion in 2020 and is expected to reach \$3.4 trillion by 2030. (Kumaand Deshmukh 2021). The continued expansion of packaged food can be ascribed to the conveniences, advancements, and benefits of packaging. One of the advantages of food packaging is that it provides information to consumers regarding the contents, shelf life, and storage conditions of the product (Singh et al. 2016). Food packaging also maintains food safety, improves the shelf life of food, and prevents food waste and loss (Verghese et al. 2015; White & Lockyer, 2020; Sasaki et al. 2022). Despite these benefits, there remain worries concerning the environmental impact of food packaging throughout its life cycle. More specifically, the extraction of raw materials for packaging materials depletes natural resources and emits additional greenhouse gases into the atmosphere (Hopewell et al., 2009). The packaging manufacturing process uses a lot of water and energy, and as a result, it produces a lot of waste and pollution (Deshwai et al. 2019). Furthermore, the existing packaging waste management industry lacks circularity because most food packaging is designed for single use and discarded after a short period of time (Geueke et al. 2018). These environmental problems caused by food packaging impede the sustainability of packed food.

Plastic is a widely used material for food packaging because it is fluid, moldable, heat sealable, easy to print, and can be integrated into production processes (Marsh and Bugusu 2007). The ING Economics Department (2019) estimates about 40% of Europe's food is packed in plastics. Over the past six decades, annual global plastic production increased sharply from two million tonnes in 1950 to 381 million tonnes in 2015. Packaging dominates primary plastics use, accounting for nearly 40% of plastic usage (Geyer et al. 2017). Particularly in the United States, the amount of plastic packaging and containers has increased gradually and reached 13 million tonnes in 2018 (EPA 2020).

Most plastic packaging materials are discarded the same year they are produced (Geyer et al. 2017). The short lifespan, together with the large volume of packaging material and the low recyclability of plastics in most regions in the world, creates a significant solid waste issue, particularly when plastics are not properly collected by waste management systems and end up in aquatic ecosystems. Consumer perceptions of plastics are generally unfavorable and plastics

are often perceived as the dominant environmental impact contributor of a product (Lindh et al. 2016; Boesen et al. 2019). Miller (2020) proposed that customers may perceive visible environmental impacts such as plastics in the ocean as more harmful than invisible effects such as energy use in the food production stages and suggested the need for holistic life cycle assessment (LCA) that quantifies and contextualizes the impact of plastic packaging relative to other processes.

LCA is an useful tool to evaluate the environmental impacts that occur in every stage along the supply chain of a product. Studies have used LCA to compare the impacts of different packaging materials for specific food products across different food categories such as liquid food (Accorsi 2015; Amienyo et al. 2013; Thoma et al. 2013), grain (Bevilacqua et al. 2007; Espinoza-orias et al. 2011), vegetables (Cellura et al. 2012), and fish (Laso et al. 2017). Licciardello (2017) examined 29 different food products' packaging relative environmental impact (PREI). Glass, steel, cartons, and aluminum, rather than plastics, make up the majority of the food packaging in the paper. Qin and Horvath (2022) looked at how packaging affects GHG emissions throughout the life cycle of fruits and vegetables. However, because only the total impact of carton boxes used in farming and plastic packaging used in retail is stated, it's difficult to know how much plastics vs carton boxes contribute. To the best of our knowledge, there is not yet a study that looks at how plastics alone contribute to the environmental impact of a variety of food items.

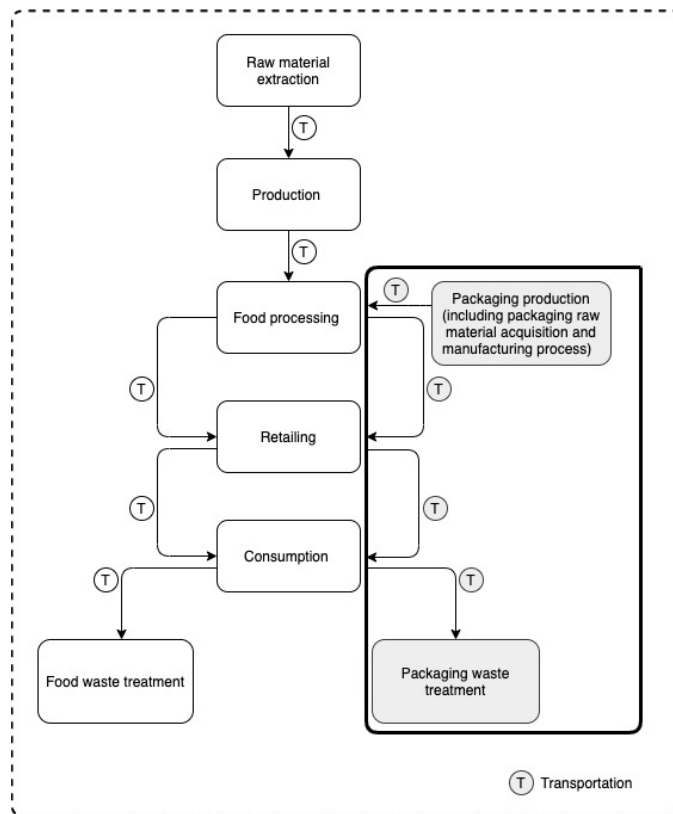
Individual studies use LCA to quantify the environmental impact of packaged food from different stages along its supply chain, but may use different boundary definitions. Some only consider the environmental impact of plastic packaging production while others extend the system boundary by including plastic packaging transportation and waste management (Molina-Besch et al., 2019). The differences in the scope of studies cause variances in the life cycle environmental impact of food packaging for the food item. To fill the research gap, this study aims to capture the total emissions throughout the lifetime of plastic food packaging to evaluate the relative impact of packaging to the total impact of the food system, comparing the trends across a variety of food categories. Also, the results of energy use and climate change are compared to a reference value of the emissions of vehicle travel in an effort to place the LCA results in better context and be more accessible to non-scientific audiences. The article is helpful for the public to understand the relative environmental impacts of both plastic packaging and food products, in an effort to better inform environmental conservation efforts.

2. Methodology

2.1 Overall approach

This study synthesizes data from literature and the Eco-invent database (Wernet et al. 2016) to capture the total emissions from packaging production, transportation, and waste management, and to evaluate the comparative environmental impact of plastic packaging within the food system. The data for the environmental impact of packaging production are extracted from peer-reviewed studies that cover a wide range of food products, in which plastic is the primary packaging material. As the scope of these studies is different, to minimize the data disparities in the transportation and waste treatment stages, we use data from the Eco-invent database to harmonize the transportation and waste management phases across a range of products to reflect the United States averages. In order to contextualize results to provide consumers with a point of reference, the results of the packaging life cycle emissions are compared vehicle travel to better understand the significance of the plastic packaging. The system boundary of this study is shown in Fig. 1.

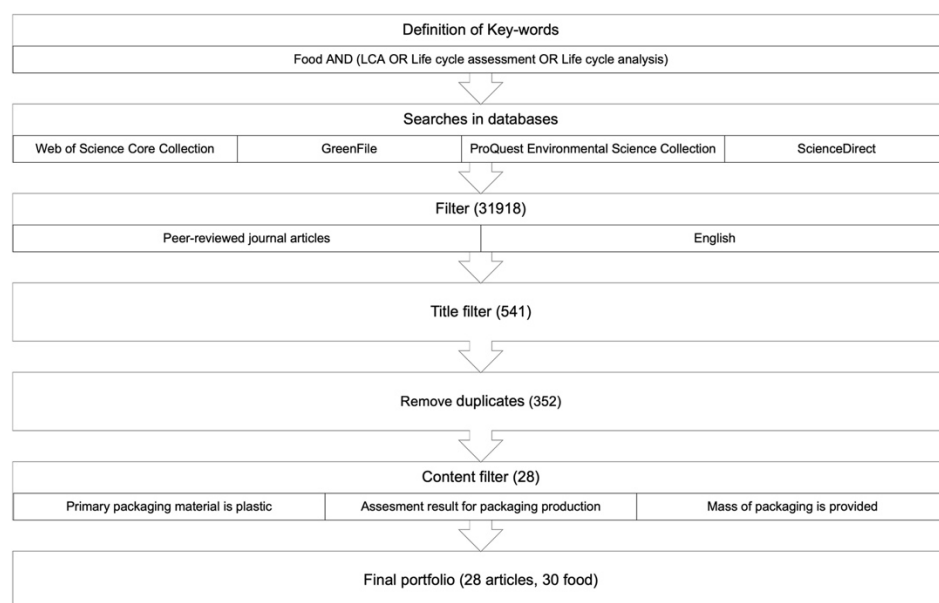
Fig. 1 System boundary of the packaging chain under analysis and general life cycle of a food system. Packaging system and food system are represented by solid and dashed boundaries, respectively. Gray boxes and circles typify the processes that contribute to the environmental impact the packaging system, the focus of this study. Packaging production data are taken from literature; packaging transportation and waste management are calculated by this study. White boxes and circles represent processes other than packaging that contribute to the environmental impact of the food system, which are also included in this study.



2.2 Literature collection

The workflow of the literature search and subsequent analysis is presented in Fig. 2.

Fig. 2 Selection of the research portfolio on LCA of food packaging



Step 1: Definition of keywords

The set of keywords to be used in the search was defined using Boolean operators, as follows:

Food AND (LCA OR Life cycle assessment OR Life cycle analysis).

Step 2: Definition of databases

For the goal of conducting a systematic literature review on LCA of plastic food packaging, four databases that cover the majority of studies in the environmental field are used: Web of Science Core Collection, GreenFile, ProQuest Environmental and Science Collection, and ScienceDirect.

Step 3: Literature search and collection

The set of keywords is used to conduct searches in the mentioned databases. The language is set as English and the document type is set as peer-reviewed journal articles. In addition to the two filters in searches, another filter is used when searching in ScienceDirect. As that database includes a variety of publications in different fields, two publications, Journal of Cleaner Production and Science of The Total Environment that are the most relevant to the topic of the present study were included; other publications such as Brain Research and Pharmacology Biochemistry and Behaviours, generally include biology and life science literature are discarded because these journals are not relevant to the present study. This idea is in line with the findings from other studies. According to the review of 172 studies about the environmental assessment of food packaging, none of the studies are from Life Science journals (Vignali 2016).

Section 4: Portfolio sorting

As the searches returned a considerable number of publications, a series of filters were applied to find the most relevant studies to be fully analyzed.

- Title filter: all remaining titles were read, and the articles considered not tightly related to the addressed topics were excluded.
- Exclusion of duplicates: EndNote X9 reference manager was used to rule out the duplicated articles.
- Content filter: In order to be included in the analysis, the study was required to have the following three characteristics.
 1. The primary packaging material is plastic.
 2. A life cycle assessment of packaging production must be included.

3. The mass of packaging material must be reported.

After applying these criteria, a final portfolio of articles was created and illustrated in Table 1. Peano et al. (2015) investigated three food items in one study, so there are two more foods than studies.

Table 1. A final portfolio of selected studies and US annual per capita consumption for the food analyzed in the study

Food	Reference of articles	US per capita consumption in 2015	Reference of consumption amount
Carbonated drink	Amienyo et al. (2013)	153.78 liter/person. yr ⁻¹	Zenith International (2019)
Tuna	Avadí et al. (2015)	7.03 kg/person. yr ^{-1 a}	USDA ERS (2019)
Carp	Biermann & Geist (2019)	7.03 kg/person. yr ^{-1 a}	USDA ERS (2019)
Crunchy chicken breast	Biswas & Naude (2016)	40.51 kg/ person. yr ^{-1 d}	USDA ERS (2019)
Dried organic pasta	Cimini et al. (2019)	7.4 kg/person. yr ⁻¹	Statista (n.d)
Italian mozzarella cheese	Dalla Riva et al. (2017)	5.12 kg/person. yr ⁻¹	USDA ERS (2019)
Milk (Iran)	Daneshi et al. (2014)	70.76 liter/person. yr ⁻¹	USDA ERS (2019)
Bread	Espinoza-orias et al. (2011)	46 kg/person. yr ^{-1 c}	IndexBox (2015)
Milk Powder	Finnegan et al. (2017)	1.36 kg/person. yr ⁻¹	USDA ERS (2019)
Butter	Flysj�� (2011)	2.54 kg/person. yr ⁻¹	USDA ERS (2019)
Frozen green bean	Ilari et al. (2019)	0.86 kg/person. yr ⁻¹	USDA ERS (2019)
Apple juice	Khanali et al. (2020)	7.15 liter/person. yr ⁻¹	USDA ERS (2019)
Canola oil	Khanali et al. (2018)	1.93 kg/person. yr ^{-1 d}	USDA ERS (2019)
Biscuit	Konstantas et al. (2019)	6.09 kg/person. yr ⁻¹	TABS Analytics (2017)

Milk (Spain)	Meneses et al. (2012)	70.76 liter/person. yr ⁻¹	USDA ERS (2019)
Rice	Mungkung et al. (2019)	9.25 kg/person. yr ⁻¹	USDA ERS (2019)
Gluten-free Biscuit	Noya et al. (2018)	6.09 kg/person. yr ⁻¹ ^b	TABS Analytics (2017)
Bottled water	Pasqualino et al. (2011)	135.90 liter/person. yr ⁻¹	International Bottled Water Association (2019)
Strawberry	Peano et al. (2015)	3.22 kg/person. yr ⁻¹	USDA ERS (2019)
Raspberry		0.36 kg/person. yr ⁻¹	USDA ERS (2019)
Blueberry		0.68 kg/person. yr ⁻¹	USDA ERS (2019)
Frozen tilapia fillet	Pelletier & Tyedmers (2010)	7.03 kg/person. yr ⁻¹ ^a	USDA ERS (2019)
Preserved plum	Romeiko et al. (2020)	0.41 kg/person. yr ⁻¹	USDA ERS (2019)
Fresh chestnut	Rosa et al. (2017)	0.49 kg/person. yr ⁻¹	USDA ERS (2019)
Cheese	Santos et al. (2017)	15.92 kg/person. yr ⁻¹	USDA ERS (2019)
Olive oil	Tsarouhas et al. (2015)	1.93 kg/person. yr ⁻¹	USDA ERS (2019)
Green asparagus	Vázquez-Rowe et al. (2016)	0.59 kg/person. yr ⁻¹	USDA ERS (2019)
Frozen octopus	Vazquez-Rowe et al. (2012)	7.03 kg/person. yr ⁻¹ ^a	USDA ERS (2019)
Almond milk	Winans et al. (2020)	4.94 liter/person. yr ⁻¹	Copeland & Dharmasena (2015)
Tomato	Maham et al (2021)	7.95 kg/person. yr ⁻¹	USDA ERS (2019)

^a Per capita fish consumption amount is used.

^b Per capita biscuit consumption amount is used.

^c Based on 2010 data; 2015 data is not available.

^dPer capita chicken consumption amount is used.

2.3 Meta-analysis

Twenty-eight articles are used to provide packaging production data for this analysis. These studies provide a breakdown of results per life cycle phase, so we only included cradle-to-gate results. Each of these studies has distinct boundaries, assumptions, and reported impact categories. Although it was impossible to account for all disparities across the studies, the same LCA assumptions for the transportation and waste management inventory data for each food product were harmonized to ensure the calculations are consistent. The assumptions are given in Section 2.4: Transportation emissions calculation and Section 2.5: End-of-life emissions calculation. For upstream production stages, it was not possible to harmonize the inventories across all foods represented in this study. Therefore, this study emphasizes relative trends in food groups and attempts to provide explanations that can be tracked to inventory assumptions or boundary definitions when data outliers are observed. For studies that reported different resolutions of impact categorization, such as “eutrophication” versus “freshwater/marine eutrophication,” indicators are grouped into thirteen impact indicators including Climate Change, Energy Use (include cumulative energy demand and primary energy demand), Ozone Depletion, Photochemical Oxidant Formation, Human Toxicity, Water Depletion, Particulate Matter, Ionizing Radiation, Acidification, and Eutrophication. Table A1 provides an additional explanation for impact categories that have been condensed to a single indicator in this analysis.

2.4 Transportation emissions calculation

This study considers four steps of transportation including transportation from packaging producer to food manufacturer, transportation from food manufacturer to retail, transportation from retail to customer, and transportation from curb to disposal plant. The distances of each step of transportation are extracted from journal articles or governmental sources. More specifically, the distance between packaging producer and food manufacturer is assumed as 200 km (Konstantas et al. 2019). Weber and Matthews (2008) estimated that the average distance between producers to the retail market in the U.S. is 1640 km. USDA estimated the distance from the retail market to customers’ homes is about 6.45 km if consumers rely on vehicles to shop groceries (Ploeg et al. 2015). The distance from curb to disposal plant is assumed as 32.19 km, which is consistent with the value used in the EPA Waste Reduction Model v15. The mode of transportation is assumed to be a diesel-powered single-unit truck, and the emission factor (E_{tkm}) of that vehicle is found in the U.S. Life Cycle Inventory Database (2012). E_{tkm} was identified for each food item, depending on the original LCA method used in literature. The calculation for transportation

emissions is given in equation 1.

$$E_T = \text{Distance} \times \text{Packaging mass} \times E_{tkm} \quad (1)$$

2.5 End-of-life (EOL) emissions calculation

End-of-life emissions are determined by waste treatment methods and the mass of packaging waste. We assume all packaging becomes waste after use and ends up recycled, incinerated, or landfilled. We multiplied the recycling, incineration, and landfill rates of post-consumption plastic materials given by EPA (2018), by the total plastic packaging mass of each food to get the quantity of packaging recycled, incinerated, and landfilled per mass unit of a food product (Equation 2). The Eco-invent database is used to obtain emission factors of each type of plastic material under the three waste management scenarios including recycling, incineration, and landfill. Three out of 27 studies indicate that the food packaging consists of two different polymers without differentiating the mass of each polymer; in this case, we assume the packaging is primarily made up of one polymer and the EOL calculation is based on the emission factor of that polymer. For the three studies that do not specify the type of plastic, we assume LDPE is used for that food packaging because that material is used most frequently for food packaging. We sum up the multiplication from the emission factor and quantity of packaging under each waste management scenario to get the total emission for EOL of that food packaging (see equation 3). Table A2 gives more information about packaging mass, plastic materials and LCA methods used to quantify environmental impact in transportation and EOL phases.

$$E_{EOL} = Q_{\text{recycle}} \times E_{\text{recycle}} + Q_{\text{incineration}} \times E_{\text{incineration}} + Q_{\text{landfill}} \times E_{\text{landfill}} \quad (2)$$

$$E_{FP} = E_P + E_{EOL} + E_T \quad (3)$$

where:

Q: quantity; E_{FP} : Environmental impact of food packaging; E_P : Environmental impact of packaging production

Table 2. Recycling rate, incineration rate, and landfill rate of plastic material in the US in 2015

Plastic material	Recycling rate (%)	Incineration rate (%)	Landfill rate (%)
Polyethylene terephthalate (PET)	24	15.2	60.8
High-density polyethylene (HDPE)	16.4	16.7	66.9
Low-density polyethylene (LDPE)	13	17.4	69.6
Polypropylene (PP)	3.8	19.2	77

Polystyrene (PS)	5.4	18.9	75.7
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Table 3. Sources of emission factor data

Data	Database
PE (waste treatment) {GLO} recycling of PE APOS, S	Ecoinvent 3 - allocation at point of substitution - system
PS (waste treatment) {GLO} recycling of PE APOS, S	
PP (waste treatment) {GLO} recycling of PE APOS, S	
PP (waste treatment) {GLO} recycling of PE APOS, S	
Polyethylene, high density, granulate {RER} production APOS, S	
Polyethylene, low density, granulate {RoW} production APOS, S	
Polyethylene terephthalate, granulate, bottle grade, at plant/RER S	Ecoinvent system processes
Polypropylene, granulate, at plant/RER S	
Polystyrene, general purpose, GPPS, at plant/RER S	
Incineration/CH S	
Landfill/CH S	

2.6 Break-even calculation

To better put the results of plastic packaging environmental impacts in context, packaging and vehicle miles traveled are compared to determine the equivalent distance where the environmental impact of packaging is equal to transportation (Equation 4). The decision was made because consumers are more familiar with the distance they travel every day than the actual environmental impact of transportation. The previous calculations for the environmental impact of packaging were normalized on a functional unit (either 1 kg or 1 liter) of a food product. However, because the packaging mass and the associated environmental impact per functional unit of food is very small, it is hard for the public to understand the extent of the impact and significance. Thus, for the break-even analysis, we use per capita annual consumption amount of each food product as the functional unit to quantify the environmental impact of packaging. The data about per capita annual consumption of food in 2015 are obtained from USDA Economic Research Service (2019) and industrial reports. More information is available in Table 1.

$$M_{BE} = \frac{E_{FP}}{E_{VT}} \quad (4)$$

where:

M_{BE} : breakeven miles; VT: vehicle travel per mile

The data about total energy consumption and emissions for every mile travel of a gasoline vehicle is from the Argonne GREET model as shown in Table 4 (Argonne National Laboratory 2019). Although the model also provides data about water consumption and particulate matter, the comparison result reports only GHG emissions and energy use due to the low number of packaging studies that provide emission information for water consumption and particulate matter.

Table 4. Emission factor of a gasoline vehicle (include feedstock, fuel, and vehicle operation)

Indicator	Amount	Unit
Energy Use	5.79	MJ/mile
Greenhouse Gas Emissions	413	grams/mile

3. Results and discussions

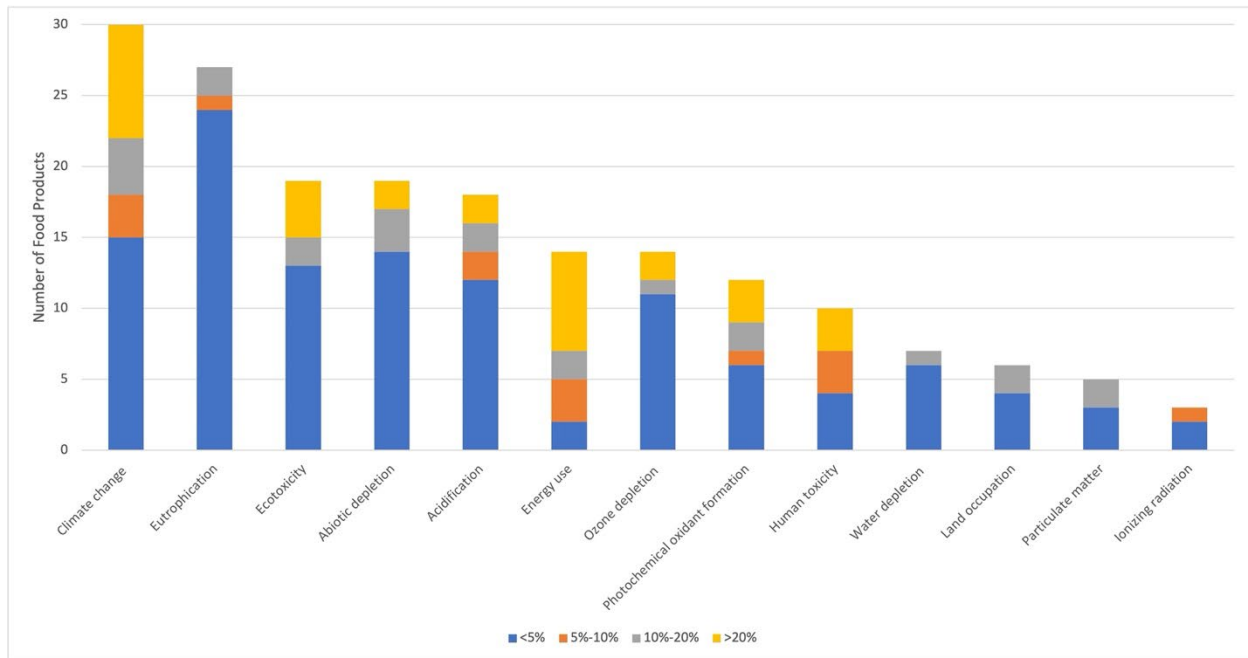
3.1 Fraction of food life cycle emissions that can be attributed to plastic packaging

By combining the extracted production emission data from literature and the calculated transportation and waste treatment data, we quantified the impact of packaging relative to the total impact along the supply chain of 30 food products for 13 environmental indicators. Of the 28 papers reviewed for this analysis, only emissions relating to climate change were reported in every study, whereas other reported environmental impacts varied in frequency across studies. Fig. 3 reports the frequency that each environmental indicator is reported across the literature studies. After climate change, eutrophication is used to measure environmental impacts the next most frequently. Ozone depletion, human toxicity, water depletion, land occupation, particulate matter, and ionizing radiation were reported in fewer than half of the studies, making it difficult to compare the contribution of the packaging to the total life cycle emissions in a fair way. Notably, current life cycle impact calculations only take into account ecosystem damage due to toxicity or eutrophication; no studies reported physical ecosystem damage associated with plastic.

In addition to reporting overall frequency of environmental indicators reported, Fig. 3 also depicts the environmental impact of packaging relative to the environmental impact of the food itself. The colored bars reveal the number of studies where plastic packaging is responsible for the associated percentage of the total environmental impact of the food products (>20%, 10-20%, 5-10%, <5%). For most environmental indicators, packaging is responsible for less

than 5% of the total environmental impact in more than half of the food products analyzed. Energy use is one environmental indicator where plastic packaging is responsible for more than 10% of total life cycle energy for the majority of food products, potentially due to the use of natural gas distillates as a feedstock to plastic production. Notably, the seven food studies (raspberries, blueberries, strawberries, carbonated drinks, almond milk, olive oil, and bottled water) that reported plastic packaging emissions that are more than 20% of the total energy use associated with that food product also report that plastic packaging is responsible for more than 20% of GHG emissions. Meanwhile, the GHG emissions from packaging are less than 10% of life cycle GHG emissions for most of the other foods analyzed. This finding is in line with Silvenius et al.'s conclusion that the carbon footprint of most food packaging from manufacturing and waste management is less than 5% of the whole food chain (2013). We anticipate that the number will rise to some extent if packing transportation is included in. Food packaging contributes 11-31 percent of life cycle GHG emissions, according to Qin & Horvath (2022), and packaging is a less important contributor to food life cycle emissions than food loss and transportation. The relative impact of packing on the entire impact of the food system from Qin & Horvath is somewhat larger than the results of this study and Silvenius et al.'s study. One explanation for the discrepancy is that Qin & Horvath's article considers both paperboard and plastic packaging, whereas our paper exclusively considers plastic packing.

Fig. 3 Number of studies in this analysis that report an environmental impact category and the percentage of environmental impact attributed to plastic packaging. The colored bars indicate the number of studies where the plastic packaging is responsible for the associated percentage of the total environmental impact of the food product.

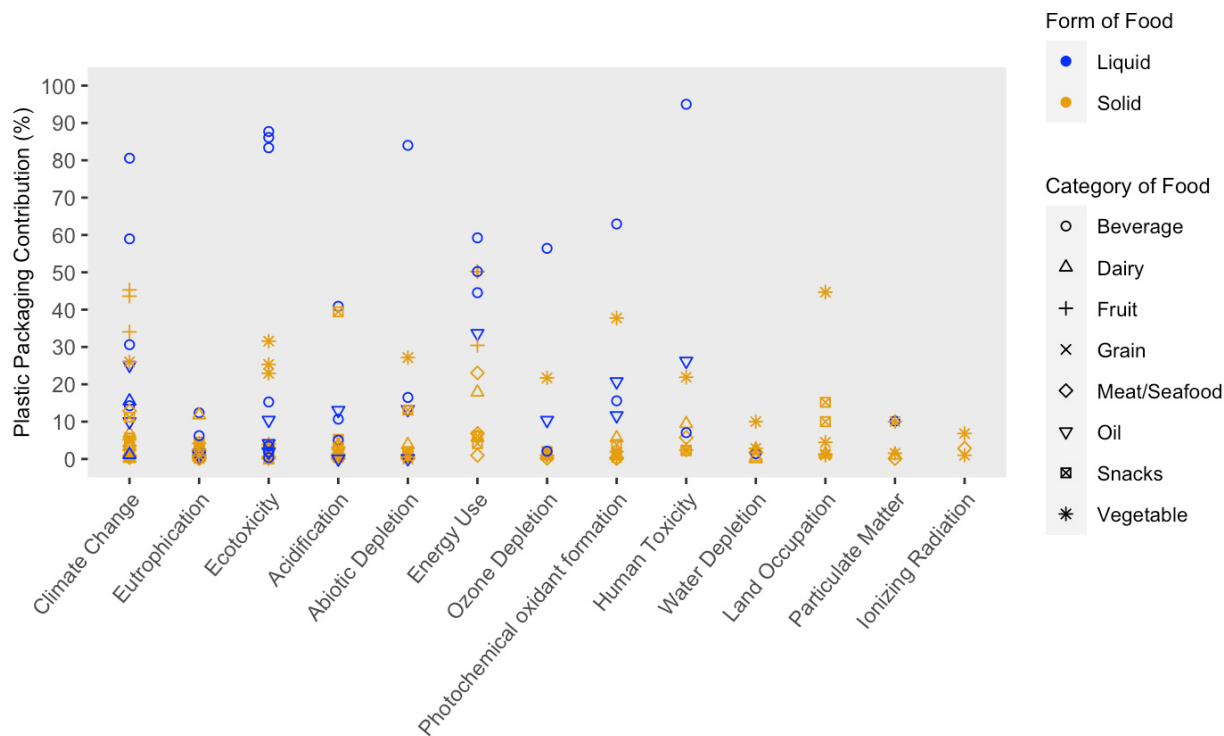


To further understand the types of food being studied and explain the variances in plastic packaging contributions across different food groups, we made two comparisons. The first one compares the environmental impact of solid and liquid food, and the second one compares the environmental impact of different food categories. In Fig. 4a, the value of each data point represents the packaging contribution to the total emissions of a food product for each environmental indicator. The different colors distinguish liquid food (blue) and solid food (yellow), and the distinct shapes represent the seven food categories. In this figure, a single food might be represented more than once for eutrophication, ecotoxicity, acidification, abiotic depletion, and land occupation if the original study provides data for a finer impact categorization of the general impact indicators. For example, Amienyo et al. (2013) measured marine ecotoxicity, freshwater ecotoxicity, and terrestrial ecotoxicity of carbonated drink packaging, the values of these three impact groups are reflected in the ecotoxicity bar of this figure.

Fig. 4a shows liquid food packaging generally has a higher impact contribution than solid food packaging. For the indicator of climate change, of the eight liquid foods (see Table 1) in the analysis, four foods have plastic contributions that are responsible for more than 20% of emissions; two foods have plastic contributions between 10-20%; the other two foods are under 10%. Meanwhile, among the 22 solid food products (see Table 1), four foods have plastic contributions that were responsible for more than 20% of emissions; two food products have plastic contributions between 5-20%; the remaining foods are under 5%. For the other indicators, the impact contribution from solid food packaging is also clustered within 0 to 10% while the range for liquid food is much wider.

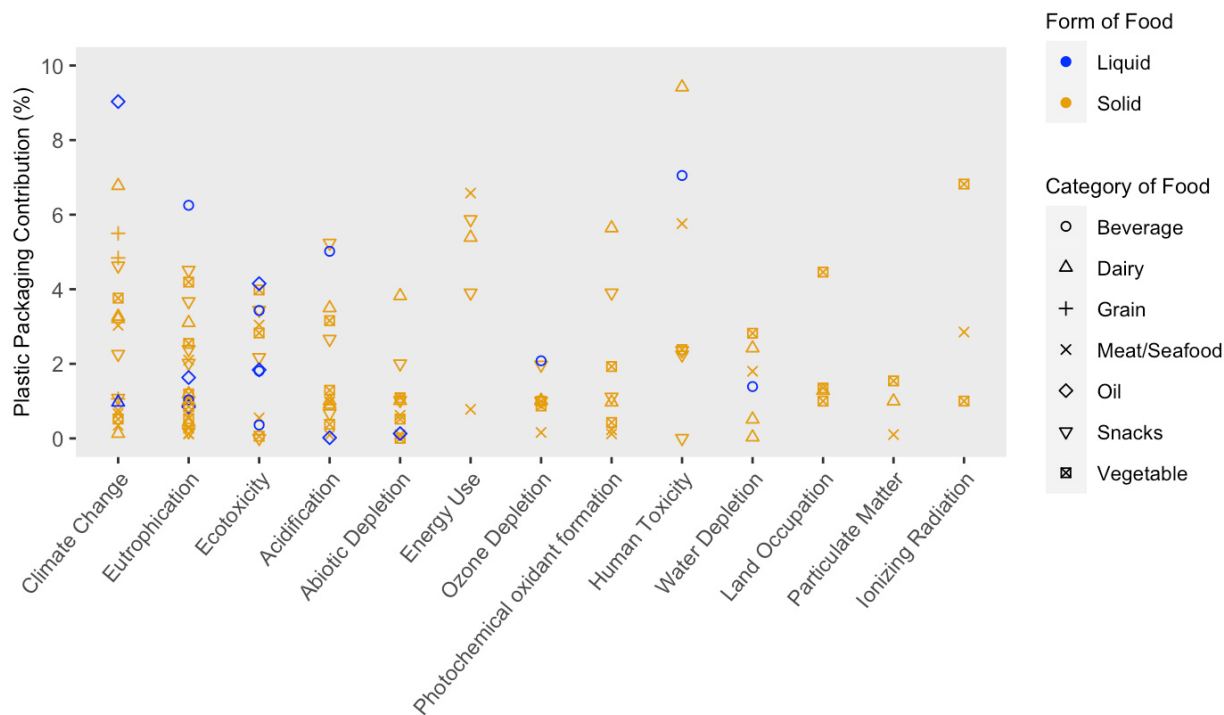
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Fig. 4a Packaging contribution (0-100%) to the overall life cycle environmental impact



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Fig. 4b Packaging contribution (0-10%) to the overall supply chain



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The finding that liquid food packaging consists of a higher environmental impact of the life cycle can be attributed to two reasons. First, the packaging materials for solid and liquid food are different. Liquid food packaging material is polyethylene terephthalate (PET), while polyethylene (PE) and polypropylene (PP) are more widely used for a variety of solid food packaging. EPA estimated that the emission of PET is 2.25 MTCO₂e/tonne, higher than the emissions of PE and PP, which are 1.68 MTCO₂e/tonne and 1.55 MTCO₂e/tonne, respectively (EPA WARM v15 2019). Thus, for the same amount of materials, PET production consumes more energy and emits more greenhouse gases than other plastic materials. The second reason is that the production processes for solid and liquid food are different. The upstream supply chain of some liquid food such as bottled water and carbonated drinks do not involve a complex agricultural process because the primary ingredient is water, with upstream environmental impacts primarily related to pumping and treating water. Pasqualino et al. (2011) showed that the water production stage has a very small influence on the total life cycle of bottled water. If water is collected from natural streams with no further treatment, the impact of water production is limited to the water bottling process. Meanwhile, solid foods have greater upstream production emissions so the overall contribution of packing would be expected to be lower.

As a food category, fruit packaging also tends to contribute a higher proportion of environmental impacts than the packaging of other food categories. The greater relative environmental impact may be due to its small packaging size relative to the amount of food product. With a smaller ratio of product volume to packaging, more packaging materials per functional unit (either 1 liter or 1 kg) of food are needed, and more GHG are emitted to produce the packaging material needed for a functional unit of food. Pasqualino et al. (2011) showed as the bottle size decreases from 1.5 L to 330 ml, packaging mass per liter of bottled water will doubles, and GHG emissions from producing that packaging will increases by 90%. Therefore, the smaller size of the packaging makes the packaging system a more significant emission source. The median product volume of most food products is 1 kg. For the three fruits included in this analysis, the product volume ranges from 125 g to 250 g. To pack one kg of the fruit, 4 - 8 individual plastic packaging boxes are needed. The total environmental impact from producing those small packaging boxes is greater than the environmental impact from producing a single larger packaging box.

3.2 Significance of environmental impact

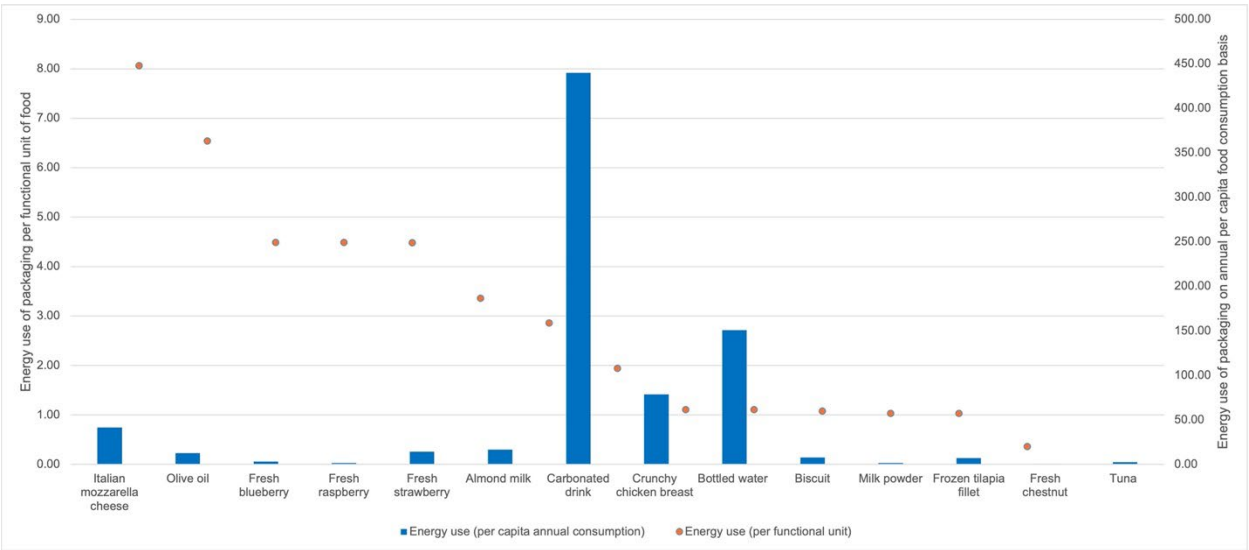
The analysis above is helpful to determine the extent of the environmental impact of plastic packaging in food products on a relative basis, but it does not depict the emissions in absolute values. A high fraction of environmental impact

contribution does not necessarily translate into a larger environmental impact. To further understand the impact of food packaging, energy use and climate change of packaging on a mass basis as well as annual food consumption basis are shown in Fig. 5a and Fig. 5b. Looking at the trends of 14 food products that report energy use data, there is a range of energy use per kg of food, with mozzarella cheese reporting the highest energy use per kg and tuna reporting the lowest. These data do not take the consumption frequency of these products into account. When the per capita annual consumption of each food is taken into account, the packaging of carbonated drinks and bottled water are an order of magnitude larger than most other products due to the ubiquity of these products. The finding suggests that the demand for different food products is a key factor affecting the total environmental impact of food packaging in a time frame. Therefore, even though the impact per individual item is in line with other food products, the overall impact of the beverage industry is quite large.

The climate change impacts of packaging shows a similar trend. The packaging impact of 1 kg butter is more than 600 g CO₂, the highest of all foods analyzed, but because the annual consumption of butter is only 2.5 kg per person, the climate change induced by the packaging from annual butter consumption is minimal. In the contrast, the annual per capita life cycle GHG emissions associated with the packaging of carbonated drinks, chicken breast, milk, and bottled water are much higher than the rest of foods analyzed because of the substantial consumption of these food products in the U.S. diet. Note that the data for the food products are not necessarily located in the United States and the two milk products included in the analysis are from Spain and Iran. Although the consumption quantity of two milk products are assumed to be the same value and the emissions for packaging transportation and waste treatment were calculated uniformly, due to the differences in their packaging mass and packaging production emissions, the milk that is produced in Spain emits more GHG than another one produced in Iran. It suggests for the same product, there are a lot of variances in different production systems. These differences highlight that while insights can be taken from overall trends in data, the results of specific product systems will vary across geography, production practice, and packaging specifics.

Fig. 5a Energy use of plastic packaging. The scatter plot shows the energy use of packaging per functional unit of food. The unit of the y-axis (left) for almond milk, carbonated drink, and bottled water is MJ/liter and for other food is MJ/kg. The bar graph shows the energy use of packaging from per capita annual consumption of the food. The unit of the y-axis (right) is MJ.

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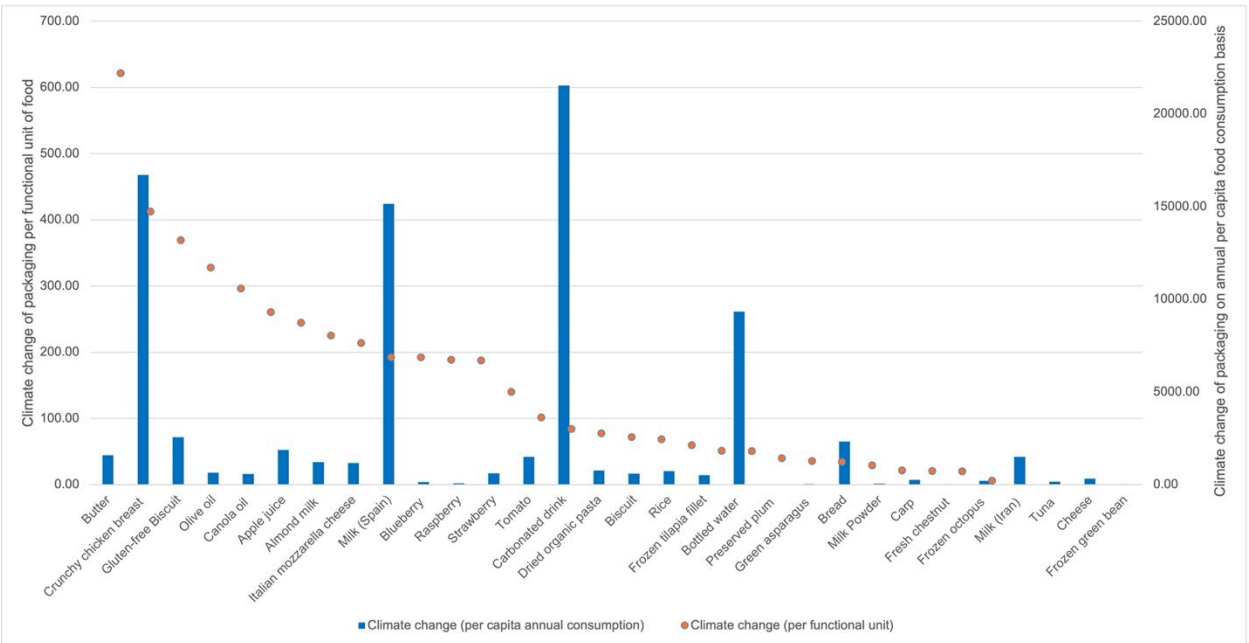
Fig. 5b Climate change (GHG emissions) of plastic packaging. The scatter plot shows the climate change of packaging per functional unit of food. The unit of the y-axis (left) for apple juice, almond milk, carbonated drink, and milk (Iran) is g co2/liter and for other foods is g co2/kg. The bar graph shows the energy use of packaging from per capita annual consumption of the food. The unit of the y-axis (right) is g co2.

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When taking annual per capita consumption of food products into account, beverages in particular seem to indicate a high contribution to overall environmental impact. Without greater context associated with LCA data, consumers may

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not have a good sense of the relative impacts of packaging compared to other environmental impacts (Miller 2020). In order to help resolve the disconnect between consumer perception of the environmental impacts of plastic and further put the results of plastic packaging environmental impacts in context, we conduct a break-even point calculation to compare the energy use and climate change of plastic packaging to the emissions associated with personal vehicle travel. Fig. 6a and Fig. 6b show the number of miles that a vehicle would need to be driven to have an equivalent impact to the annual per capita consumption of packaging materials for each food type. Annual consumption of carbonated beverages, which represent the most impactful packaging category on an annual basis, are equivalent to the energy use associated with 76 miles of gasoline vehicle travel and the GHG emissions of 52 miles of travel. According to the AAA Foundation for Traffic Safety's 2015 American Driving survey, the average driver in the US drives 30 miles each day (Tefft, B.C., 2018). This means the energy use of the packaging of annual carbonated drinks consumed by a person is equivalent to less than 3 days of vehicle travel energy use and less than 2 days of travel with respect to climate change. Of all of the foods analyzed, carbonated drinks is the only packaging type equivalent to greater than one day of vehicle energy use, while carbonated drinks, chicken, and milk (assuming Spanish production assumptions) are the only types of packaging to exceed the equivalent of one day of travel-associated GHG emissions. For most food products, the energy use and climate change induced by annual per capita packaging is small, equivalent to the energy used to drive for a few miles or less.

Fig. 6a Break-even miles at which energy use of food packaging equals the energy use of vehicle transportation

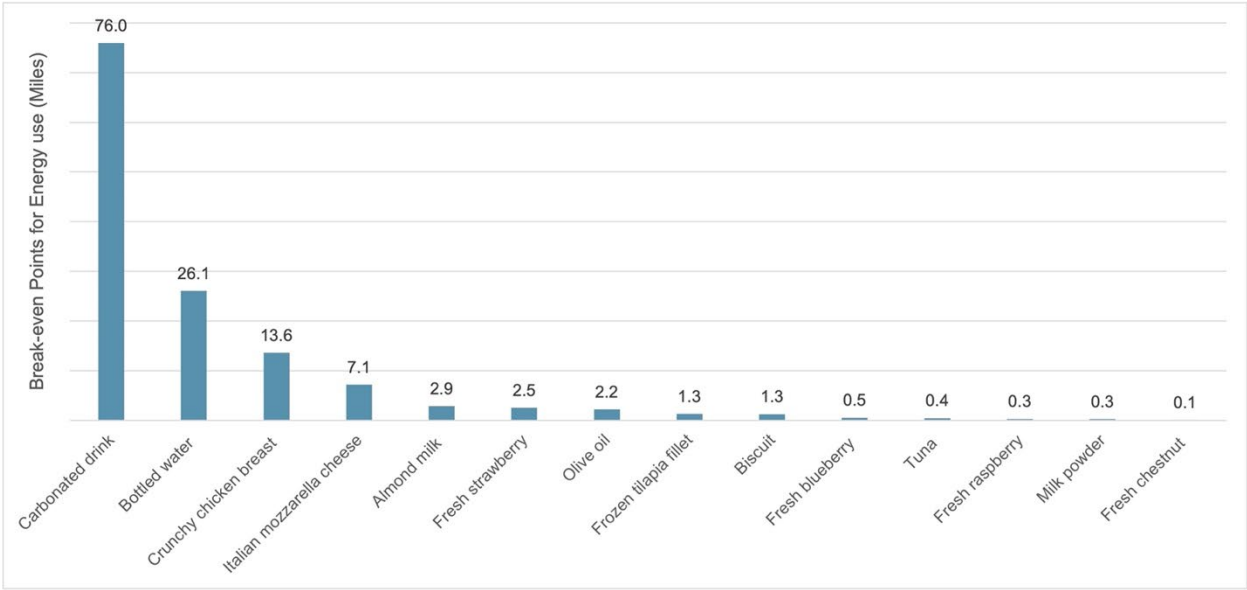
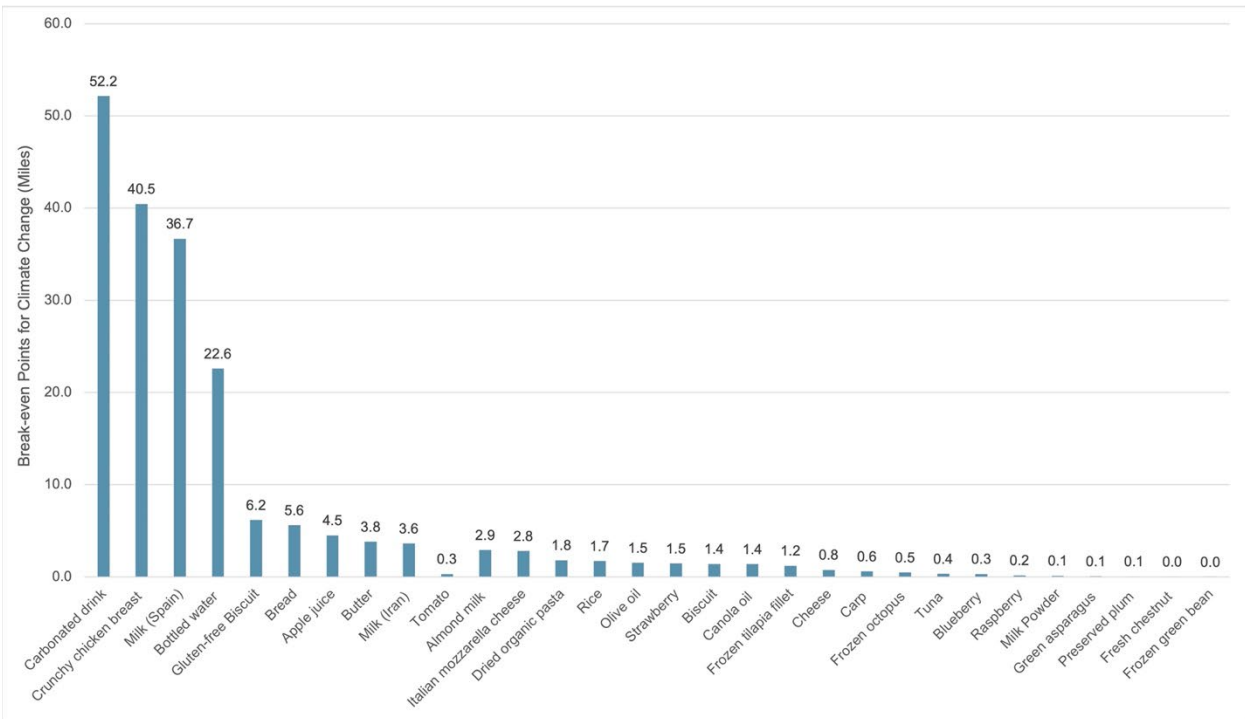


Fig. 6b Break-even miles at which climate change of food packaging equals climate change of vehicle transportation



4. Conclusion

In this study, we quantified the fraction of total life cycle emissions that can be attributed to plastic packaging using a variety of perspectives. We found that packaging is not a dominant environmental impact source for the majority of the 30 foods analyzed, although there are significant differences in the overall trends between liquid and solid food products as well as across food categories. For most environmental indicators, the packaging system of most food accounts for less than 10% of total emissions, while other possesses in the food system are more significant environmental impact contributors.

We also found the demand for different food products is a key factor affecting the total environmental impact of food packaging. For example, the environmental impact per functional unit of butter and oil are more significant than other food, due to the small consumption quantity, their environmental impact based on annual consumption is less significant compared to other foods which are consumed more frequently. The break-even calculation compares the energy use and GHG of food packaging with vehicle travel to help the public interpret the LCA results and understand the significance of packaging impact. The results show that for the majority of food products, the environmental impact caused by per capita annual food packaging is less than that of per capita daily vehicle travel.

The study presents some limitations. First, the data for the food products are not necessarily located in the United States, instead, we obtained plastic production data from studies conducted from all over the world. In different regions, the packaging production system can be very different and the environmental performance from producing the plastic packaging vary as well. Future studies may focus on collecting data in a specific region to reduce data disparities. Second, this study only includes studies that focus on LCA of packaged food. Some other studies which compare the impact of different packaging system on food may provide useful data are not included in this study. Therefore, future studies may try different groups of search keywords to build a more comprehensive literature database. Also, out of 14 studies that reported energy use of plastic production, five studies reported primary energy demand, eight studies reported cumulative energy demand, and one study simply used the term “energy consumption” to describe energy use. We were not able to convert values in three different metrics to a same metric. Thus, we acknowledge errors in plastic production phase caused by the inconsistent metrics, but we believe the errors are very small. For plastic transportation and EOL phase, we used cumulative energy demand to indicate energy use. Lastly, we conducted the break-even analysis for only two environmental indicators, climate change and energy use, because low number of packaging studies provide emission information for water consumption and particulate matter. Future LCA studies should increase the use of indicators in addition to climate change and energy use to help capture the overall environmental impact of plastic packaging.

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