



Exploring the total cost of whole fresh, fresh-cut and pre-cooked vegetables

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Abstract

Purpose The food industry should evolve towards new business models which take into account the damage cost in decision making, considering the impact that its products generate on the natural and human environment. Hence, the present study aims to calculate the damage cost caused by the production of whole fresh (as average of potatoes, aubergines, and broccoli), and processed vegetables (fresh-cut and pre-cooked).

Methods The environmental life cycle approach was carried out per kilogram of assessed products (from cradle to the entrance of the market). The foreground Life Cycle Inventory was obtained from engineering procurement and construction projects of the whole fresh and processed vegetables industries. The Ecoinvent 3.8 and Agribalyse 3.0.1 databases were used for the background inventory. The ReCiPe 2016 method was used with a hierarchical perspective, evaluating eighteen midpoint categories as well as the endpoint categories (human health, ecosystems, and resources). The monetisation of these environmental impacts was then calculated using the endpoint monetisation factors developed by Ponsioen et al. (Monetisation of sustainability impacts of food production and consumption. Wageningen Economic Research, Wageningen, 2020) for each product. It should be noted that this study does not include a comparative assessment. This study does not intend to compare the results for the three vegetable groups.

Results and discussion The damage costs were 0.16 €/kg for whole fresh vegetables, 0.37 €/kg for fresh-cut vegetables and 0.41 €/kg for pre-cooked vegetables. The agricultural production stage contributed most to these total damage costs due to the impact produced on land use and global warming in midpoint categories and human health and ecosystems in endpoint categories. In addition, the damage cost due to fossil resource scarcity (midpoint) and resource scarcity (endpoint) was mainly caused by the plastic packaging of fresh-cut and pre-cooked vegetables. The total cost was 1.02 €/kg for whole fresh vegetables, 2.99 €/kg for fresh-cut vegetables, and 3.43 €/kg for pre-cooked vegetables.

Conclusions These results suggest that some efforts should be made to reduce both environmental impacts and damage costs. For instance, to improve agricultural production, special attention should be paid to fertilisation and water consumption. Additionally, new packaging options should be explored as well as the inclusion of renewable sources in the electricity grid, and finally, on transporting the finished products to the market, by using trucks that run on cleaner fuels.

Keywords Life Cycle Assessment (LCA) · Total Cost Accounting · Damage cost · Agriculture · Post-harvest · Endpoint damage · Weighting · Monetisation

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Highlights

- Vegetables farming stage was the main contributor to environmental impact.
- Agricultural stage was the main driver of the damage costs.
- Damage cost on human health was dominated by global warming and land use.
- The damage costs ranged from 12.0 to 15.6% of the total costs.
- Damage cost reduction potential identified for the studied vegetable groups.

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1 Introduction

Society's shift towards an increasingly hectic lifestyle has affected eating habits, with increased consumption of ready-to-eat convenience foods (Wolfson et al. 2016; Halkier 2017). Vegetables are rich in bioactive compounds such as vitamins, minerals and antioxidant compounds that help to provide a healthy diet. Some options to increase vegetables intake include the consumption of fresh-cut and pre-cooked vegetables. Fresh-cut products (also known as the fourth range) refer to any fruit or vegetable, or combination thereof, which has been physically altered (trimmed, washed, sliced,

chopped, peeled, and/or cut, etc.) but is usually sold fresh and packaged. Pre-cooked vegetable products (also known as the fifth range) have been subjected to physical alteration (as above) followed by additional processing (e.g., steaming, grilling or other type of transformation) before being packaged (vacuum or modified atmosphere) for extended shelf life. Pre-cooked products normally use heat-resistant packaging to facilitate domestic reheating in conventional or microwave ovens prior to consumption by the end-user. In general, both fresh-cut and pre-cooked vegetables require refrigeration during storage and distribution.

The review focuses primarily on the last two decades. There is widespread concern that food products are becoming increasingly unsustainable (Willett et al. 2019). The food industry contributes to 21–37% of the carbon footprint, a figure that is expected to increase to 30–40% by 2050 if appropriate measures are not taken (Trolle et al. 2022). Furthermore, food production contributes to other impacts such as biodiversity loss, land and ecosystem degradation, water availability (EEA 2022), acidification and eutrophication (Poore and Nemecek 2018).

Life cycle thinking has been advocated as a reference method to analytically determine those impacts (Notarnicola et al. 2017). Thus, several researchers determined the environmental life cycle assessment (E-LCA) of different food products. For instance, Clune et al. (2017) gathered 140 whole fresh vegetables grown in open field and reported an average carbon footprint of 0.47 kg CO₂ eq/kg. Giovenzana et al. (2021) determined the environmental impact of fresh-cut salad, obtaining a carbon footprint of 2.5 kg CO₂ eq/kg. The main contributor to the impact was the vegetable processing stage (mainly due to the wastewater produced during the washing process). For that reason, Fusi et al. (2016) reported reclaimed water use to mitigate that impact and improve the environmental performance of fresh-cut vegetable production. Likewise, Vigil et al. (2020) focused on the vegetable washing stage in order to assess the environmental impact of different sanitisation techniques and determine which one could lead to the highest savings. On the other hand, Rasines et al. (2023) obtained a carbon footprint of 0.75 kg CO₂ eq/kg of fresh-cut vegetables, reporting that the main contributor was the production of the raw vegetables (vegetable farming); to mitigate the impact on that stage they proposed practices such as reducing water consumption and organic fertiliser use.

The carbon footprints reported in the literature for pre-cooked products varied widely, as each paper included ingredients of a different nature. For instance, Sieti et al. (2019) evaluated the environmental impact of baby ready meals, obtaining a carbon footprint that ranged from 1.1 to 5.5 kg CO₂ eq/kg. Schmidt Rivera and Azapagic (2019) evaluated the environmental impact of different marketed pre-cooked products, obtaining a

carbon footprint that ranged from 5.8 to 13.9 CO₂ eq/kg. Likewise, San Miguel and Ruiz (2021) calculated the environmental impact of a pork and bean stew, obtaining 2.2 kg CO₂ eq/kg. Those studies showed ingredient production to be one of the greatest contributors to the environmental impact, which was even higher for those recipes containing meat-based products.

However, the sustainability assessment should not be limited to the environmental damage, since food production also has effects on society, human well-being, food security, social inclusion, or the economy (Hoek et al. 2021). Thus, the life cycle costing (LCC) tool was developed to incorporate the economic dimension into the decision making process (Hoogmartens et al. 2014). For instance, Schmidt Rivera and Azapagic (2016) compared the environmental and economic impact of pre-cooked and home meals. Nevertheless, that study did not cover the total cost, which should include the externalities or damage cost of the environmental impact in order to calculate the total production cost (internal and damage cost) (Hoogmartens et al. 2014). Dascălu et al. (2009) argued on the need to consider those total costs (including damage cost) in the sustainability assessment.

Damage costs refer to the expenses incurred because of direct environmental impacts. These costs are a part of the cost borne by economic agents in environmental accounting (United Nations 2023). The market prices of the goods or services being exchanged do not reflect these damage costs and benefits, thereby leading to market inefficiencies (Pizzol et al. 2015). Through monetisation, damage costs are obtained by the conversion of physical environmental impacts into monetary values which represent a share of the non-internalised costs (Morel et al. 2018). The monetary valuation has great potential to enable the environmental, social, and economic assessments to be joined together and thus obtain a single value combining all three (Pizzol et al. 2015). Moreover, it could be a useful instrument to support organisations in developing more sustainable business models and practices as per ISO 14008 (2019a), since the categories generating the greatest impact can be identified through monetisation and thereby enable comparison between products in terms of environmental costs (Isacs et al. 2016).

Damage costs can be quantified following standardised procedures, such as ISO 14007 (2019b) which provides the guidelines for an organisation to determine the costs and benefits associated with their environmental performance. ISO 14008 (2019a) provides a methodological framework for the monetary valuation of related environmental impacts and related environmental aspects, as well as the requirements and recommendations for monetary value determination and documentation. Additionally, ISO 14054 (2023), currently under development, is intended to provide guidance for the process of preparing natural capital accounts; this is a systematic method to combine

financial, socioeconomic and environmental performance of an organisation's impact.

However, several methods to monetise the environmental impacts exist and as yet there is no agreement on the most appropriate monetisation method (Ponsioen et al. 2020; Canaj et al. 2021b). For instance, Arendt et al. (2020) and Amadei et al. (2021) compared numerous monetising methods and both agreed that there is great variability in monetary factors between methods, with from two to five or from one to three orders of magnitude, respectively. Arendt et al. (2020) also identified regionality as another factor of variability, and additionally Amadei et al. (2021) identified climate change and fossil and mineral and metals resource use as having the highest monetisation factor compared to other categories.

Researchers have determined the damage cost of different agricultural productions. Wagner et al. (2022) evaluated the environmental impact of miscanthus cultivation using the Environmental Footprint (EF) (Zampori and Pant 2019) method and employed monetising factors to obtain the damage cost (European Commission 2020). They found that climate change, land use and particulate matter formation were the most influencing impact categories on the damage cost. Likewise, Canaj et al. (2021a) assessed the damage cost of fruit and vegetable cropping using reclaimed water with the ReCiPe method and Ponsioen et al. (2020) monetising factors, obtaining damage costs that ranged from 0.06 €₂₀₁₈/kg for tomato to 0.21 €₂₀₁₈/kg for artichoke, with a contribution of 57% and 38%, respectively, to the total cost. On the other hand, Saxe et al. (2019) calculated the damage costs of a meal service catering. That work used the Stepwise 2006 v1.05 method (Weidema 2009; Pizzol et al. 2015) to monetise the environmental impact, and reported a mean value of damage costs of 0.77 €₂₀₁₉/kg meal, where the climate change impact category was the environmental impact which contributed the most to the damage costs (48–49%).

In light of the above, the present study aims to monetise the LCA (Life Cycle Assessment) results of whole fresh, fresh-cut, and pre-cooked vegetables (from cradle to the entrance of the market) to calculate the damage cost of these products. The total cost was calculated by adding the damage cost to the internal cost. The whole fresh vegetables were studied (as an average of potato, aubergine, and broccoli), while the fresh-cut and pre-cooked product consisted of different mixes of vegetables (cauliflower, broccoli, green bean, fava bean, carrot, onion, potato, leek, celery, and aubergine). This assessment was used to answer the following research questions: a) What are the damage and total costs of whole fresh, fresh-cut, and pre-cooked vegetables? b) Which impact categories contribute the most to the damage cost? It needs to be noted that this study does not intend to compare the results for the three vegetable groups.

The research carried out presents useful perspectives for the fruit and vegetable industry since it integrates both the economic and the environmental impact of the fruit and vegetable industries in economic terms, which is helpful for decision making on improving the sustainability of these products. In addition, this work shows the total cost of production of whole fresh and processed (pre-cut and pre-cooked) vegetables to the market entrance, which has not been previously explored in the literature. Finally, some recommendations have been provided to improve their environmental impact and therefore the damage cost.

2 Methodology

2.1 Assessment framework

The work was carried out in three stages. The first involved the environmental analysis of food products (whole fresh, fresh-cut, and pre-cooked vegetables) using a life cycle approach. The second step involved the monetisation of these impact values to determine their worth in economic terms. The environmental analyses were carried out according to standards ISO 14040/44 (2006a, b) and modelled using SimaPro 9.3 software (PRé Consultant 2022). The damage costs were calculated using the endpoint monetisation factors developed by Ponsioen et al. (2020) for midpoint and endpoint impact categories. Thirdly, in order to obtain the total costs (Fig. 1), the damage costs have been added to the internal cost calculated by LCC.

2.2 Scope definition

2.2.1 System description and system boundaries

The present work studied the production of three whole fresh vegetables (potato, aubergine, and broccoli) and two processed products (fresh-cut and pre-cooked vegetables). It should be noted that these three whole vegetables were part of a set of 10 vegetables analysed by Rasines et al. (2023), which included cauliflower, broccoli, green bean, fava bean, carrot, onion, potato, leek, celery, and aubergine. The selection of the three vegetables was based on their carbon footprint, to provide a diverse representation of their environmental impact, including those with low, medium, and high carbon footprints. The results of the whole vegetable group are given for the unweighted average of three selected whole fresh vegetables (potato, aubergine, and broccoli).

The same boundaries, cradle to market entrance, were applied to all products (Fig. 2). The following main stages were considered: a) Upstream stage, which included the vegetable farming, the production of packaging materials, sauces and auxiliary materials (disinfectants and detergent);

For both industries, the vegetables were transported 30 km to the factory. The assessment for the whole fresh vegetable industry (1) of potato, aubergine, and broccoli began with a mechanical sorting, with around 17% of fresh vegetables being discarded (biowaste) for failing to meet quality standards. Then the fresh vegetables were packed in bulk in reusable polypropylene plastic crates, palletised, and put into cold storage until they were transported to the market (500 km) using 16–32 t diesel-powered trucks. In addition, a processed vegetables industry (2) was also studied, which produces different vegetable mixes of fresh-cut vegetables and pre-cooked vegetables with different packaging weights (0.4–0.8 kg). The following vegetables were used in that factory: cauliflower, broccoli, green bean, fava bean, carrot, onion, potato, leek, celery, and aubergine. Sauces (oil and bechamel) were only required for the pre-cooked vegetables. The factory that produced the processed vegetables had a main processing line for selecting, cutting, and/or peeling and/or cleaning, disinfecting and centrifugating the vegetables as well as their cold storage. They were subsequently used in the production of fresh-cut or pre-cooked vegetables. This mix of cut and cleaned vegetables was dosed in trays to be marketed as fresh-cut vegetables. In addition, to produce pre-cooked vegetables, these cut and cleaned vegetables were blanched and drained, dosed in bags or plates with the incorporation of sauces and heat treated (90 – 120 °C). The processed vegetable industry had a higher food waste average (30%) than the whole vegetable industry, due to the removal of inedible parts in the processing stage, as well as the need for additional wastewater management. Finally, both processed products (fresh-cut and pre-cooked) were packaged in polypropylene reusable plastic crates and palletised for cold storage until their distribution. Lastly, both products were transported by road (500 km), from the factory to the entrance of the market, using 16–32 t diesel-powered trucks. The waste management shares for all the packaging materials were obtained from (MITECO 2019).

2.2.2 Functional unit

The functional unit (FU) was 1 kg of finished product (either whole fresh, fresh-cut, or pre-cooked vegetables) at the entrance gate of the market (the 1 kg was without packaging) in line with Product Category Rules (PCR) (EPD System 2019a, 2020). Note that in the specific case of pre-cooked vegetables, sauces are included in this kilogram of finished product. Furthermore, it should be noted that the majority of food-based LCA, as shown in the reviews conducted by Cerutti et al. (2014) and Parajuli et al. (2019), use a mass-based functional unit. This FU facilitates the comparison between different products within the scope of our analysis.

2.2.3 Allocation and multifunctionality

Two different factories were included in this study, one was engaged in the production of whole fresh vegetables (potato, aubergine, and broccoli) and the other factory was involved in the production of processed products (fresh-cut and pre-cooked vegetables). A mass allocation was used to determine the building and machinery requirements of the assessed products, and this was also used for the processed products to assign electricity consumption and biowaste burdens among fresh-cut and pre-cooked products.

For the whole fresh and both the processed vegetable products, the biowaste produced during harvest was supposed to remain in the field and turn into compost naturally. Thus, the production and use of chemical fertilisers such as ammonium nitrate was reduced. This substitution was made considering the ratio of the N content (1:1) (Keng et al. 2020). On the other hand, the vegetable biowaste produced in the factory was used as a substitute for maize in animal feed. The saving associated with this replacement was calculated according to Rasines et al. (2023). For that purpose, the nutritional value on fresh weight of the maize was taken to make this conversion (USDA 2021). For environmental LCA, the UNE-EN 15084 (2012) was followed to determine the savings from packaging recycling, as suggested by the Product Category Rule of packaging (EPD System 2019b).

2.2.4 Environmental life cycle impact assessment (LCIA)

The ReCiPe 2016 method with a hierarchist perspective was used (Huijbregts et al. 2017) to calculate eighteen midpoint categories, and three endpoint categories at damage level (human health, ecosystem quality, and resource scarcity).

Regarding the damage impact categories, DALY (disability adjusted life years) describes the equivalent years lost due to illness, disability, or death. The unit for ecosystems damage is in species per year and describes the local species loss integrated over time. The unit for resource scarcity is in USD₂₀₁₃, which represents the extra cost involved for future mineral and fossil resource extraction (Huijbregts et al. 2016).

2.2.5 Inventory data collection

The foreground inventory was obtained from two private Engineering Procurement and Construction Management projects. One project focused on the production of whole fresh vegetables, whilst the other one involved the production of fresh-cut and pre-cooked vegetables. The background inventory of electricity, packaging, auxiliary materials, transport, and waste management comes from Ecoinvent 3.8 (Ecoinvent 2021). Almost all vegetable production comes from Agribalyse 3.0.1 (Asselin-Balencçon

et al. 2020). More specifically, the background inventories of some vegetables were adjusted to comply with current regulations on the use of phytosanitary products on crops, replacing banned phytosanitary substances for other ones with similar activity (MAPA 2022a). The Spanish electric mix of Ecoinvent 3.8 (Ecoinvent 2021) was updated to 2021.

2.3 Life cycle inventory (LCI)

The inventory related to vegetable farming is described in the supplementary information (Table SI1). Table 1 shows the Life Cycle Inventory (LCI) flows of the whole fresh and processed vegetables. According to that inventory,

1 kg of whole fresh vegetables required 1.26 kg of vegetables considering the biowaste (9% vegetable loss in the field and 17% in the industry). For fresh-cut and pre-cooked products the figures were 1.43 kg and 1.34 kg, respectively. The demand for vegetables for pre-cooked products was lower, as the functional unit (1 kg) included the weight of sauces. Therefore, the weight of vegetables in the finished product (at the entrance of the market) was the same for whole fresh and fresh-cut vegetables (1 kg), whilst for pre-cooked vegetables it was 0.94 kg since it included the sauces (0.06 kg). The pre-cooked vegetables were the only ones that needed sauces (oil or bechamel), which increased the transport demand. As mentioned before, the fresh-cut and pre-cooked vegetables required

Table 1 Life cycle inventory of finished whole fresh, fresh-cut, or pre-cooked vegetables (all data refers to 1 kg of product at the entrance gate of the supermarket)

				Fresh whole vegetables ^a	Processed vegetables ^b		Unit	
				Fresh-cut	Pre-cooked			
UPSTREAM	Vegetable farming	Agricultural production*		1.26E+00	1.43E+00	1.34E+00	kg	
		Biowaste: Vegetable loss in the field		9.00E-02	1.17E-01	1.11E-01	kg	
	Sauces	Bechamel		-	-	4.00E-02	kg	
		Oil		-	-	2.00E-02	kg	
	Packaging materials production	Primary packaging	HDPE bins		8.70E-04	2.40E-03	2.40E-03	kg
			PP tray		-	2.75E-02	1.95E-02	kg
			PP plate		-	-	1.95E-02	kg
			PE/EVOH/PE film		-	4.71E-02	4.71E-02	kg
		Secondary packaging	PP bags		-	-	1.61E-03	kg
			Cardboard		-	-	3.00E-02	kg
			PP crates		1.29E-03	2.49E-02	2.84E-02	kg
			Tertiary packaging	PP film		2.08E-04	6.94E-04	6.00E-04
	Wooden pallet			6.51E-02	1.81E-02	1.55E-02	kg	
	Auxiliary materials	Chlorine		-	1.01E-02	9.53E-03	L	
		Detergent		-	3.00E-03	3.00E-03	kg	
CORE	Vegetable processing	Fabrication	Building		2.88E-05	1.19E-04	1.19E-04	m ²
			Machinery		1.07E-04	7.33E-03	7.33E-03	kg
		Transport of materials to factory	Transport of materials to factory		3.85E-02	6.34E-02	6.54E-02	tkm
		Energy consumption	Electricity		2.54E-02	8.00E-01	1.01E+01	kWh
		Water consumption	Water		-	9.35E+00	1.30E+01	L
		Waste treatment	Wastewater		-	8.45E+00	1.30E+01	L
			Biowaste: Vegetable loss in the industry		1.70E-01	3.00E-01	2.80E-01	kg
DOWNSTREAM	Transport	Transport to supermarket		5.33E-01	5.59E-01	5.71E-01	tkm	
	Packaging waste treatment	Packaging materials		5.33E-01	1.21E-01	1.45E-01	kg	

^aFresh whole vegetable as average of potato, aubergine, and broccoli

^bVegetables used for fresh-cut and pre-cooked products: cauliflower, broccoli, green bean, fava bean, carrot, onion, potato, leek, celery, and aubergine

*Agricultural production, including the vegetable loss in the field (upstream biowaste) and the vegetable loss in the industry (core biowaste) required for 1 kg of product at the entrance gate of the supermarket

washing and chlorine disinfection plus specific steps for processing (cutting, peeling, centrifugating, etc.). Those products therefore had greater electricity demands than the whole vegetables. Furthermore, in contrast to whole fresh vegetables that only required reusable plastic crates during transportation to market, the processed vegetables used more packaging items (trays, plates, bags, cardboard). In contrast, the whole fresh vegetables were mechanically sorted and packaged in bulk in plastic crates, which entailed lower electricity and materials needs for packaging. Overall, all the packaging (primary, secondary, and tertiary) amounted to 6.75E-2 kg for whole fresh vegetables, 1.21E-1 kg for fresh-cut vegetables, and 1.65E-1 kg for pre-cooked vegetables (Table 1).

2.4 The monetisation of LCA impacts: damage costs

As previously mentioned, the damage costs were calculated using the monetisation factors developed by Ponsioen et al.

(2020) and updated to €₂₀₂₁ using the general inflation rates for Spain reported by INE (2022). Moreover, the USD₂₀₁₃ of damage due to resource scarcity were transformed into €₂₀₁₃ (1 €₂₀₁₃ = 1.3281 USD₂₀₁₃) (CAMBIOEURO 2023). The monetisation factors used in this research are summarised in Table 2.

2.5 Total cost

The average internal cost of whole fresh vegetables at the market entrance was obtained from the Spanish Ministry of Agriculture, Fisheries and Food (MAPA 2022b). These costs were obtained from the weighted average weekly reports produced at national level, which cover approximately 80% of national production. On the other hand, the internal cost of processed vegetables (fresh-cut and pre-cooked) at the supermarket entrance was obtained from Rasines et al. (2023). Thus, the costs of selected whole fresh vegetables were: 1.03 €₂₀₂₁/kg whole fresh vegetables, as the unweighted average of single vegetables: 0.97 €₂₀₂₁/kg

Table 2 Monetisation factors based on endpoint for midpoint and endpoint impact categories

Midpoint impact categories ^a	Emission units	€ ₂₀₂₁
Global warming, human health	kg CO ₂ eq	6.70E-02
Global warming, ecosystems	kg CO ₂ eq	3.20E-02
Stratospheric ozone depletion	kg CFC ₁₁ eq	3.80E+01
Ionizing radiation	kBq Co-60 eq	6.10E-04
Ozone formation, Human health	kg NO _x eq	6.60E-02
Fine particulate matter formation	kg PM _{2.5} eq	4.50E+01
Ozone formation, Terrestrial ecosystems	kg NO _x eq	9.30E-03
Terrestrial acidification	kg SO ₂ eq	2.40E+00
Freshwater eutrophication	kg P eq	7.70E+00
Marine eutrophication	kg N eq	5.80E-03
Terrestrial ecotoxicity	Kg 1,4-DCB	1.30E-04
Freshwater ecotoxicity	Kg 1,4-DCB	8.00E-03
Marine ecotoxicity	Kg 1,4-DCB	1.20E-03
Human carcinogenic toxicity	Kg 1,4-DCB	2.40E-01
Human non-carcinogenic toxicity	Kg 1,4-DCB	1.60E-02
Land use	m ² a crop eq	1.00E-01
Mineral resource scarcity	kg Cu eq	2.00E-01
Fossil resource scarcity	kg oil eq	3.90E-01
Water consumption, human health	m ³	1.60E-01
Water consumption, ecosystems	m ³	1.60E-01
Endpoint impact categories	Damage units	€ ₂₀₂₁
Human Health ^a	DALY	7.55E+04
Ecosystems ^a	Species-yr	1.21E+07
Resources ^b	USD ₂₀₁₃	8.30E-01

Monetisation factors based on endpoint for midpoint and endpoint impact categories (Ponsioen et al. 2020) updated to 2021

^aThe monetisation factors were updated with the Consumer Price Index (CPI) which increased by 4.8% from 2017 to 2021

^bValues for resources have been recalculated to adapt 1 USD₂₀₁₃ to €₂₀₂₁. The equivalence was 1 €₂₀₁₃ = 1.3281 USD (CAMBIOEURO 2023) and the Consumer Price Index (CPI) rose by 10.2% from 2013 to 2021

of potato, 0.68 €₂₀₂₁/kg of aubergine, and 0.93 €₂₀₂₁/kg of broccoli. The costs for processed vegetables were 2.62 €₂₀₂₁/kg of fresh-cut vegetables and 3.02 €₂₀₂₁/kg of pre-cooked meals. Total costs were calculated as the sum of internal costs and damage costs.

3 Results and discussion

3.1 Life cycle impact assessment at midpoint level

The characterised midpoint impacts per functional unit are shown in Table 3. The cells are coloured from green to red. The environmental impact of whole fresh vegetables was obtained from the mean environmental emissions of potato, aubergine, and broccoli. The carbon footprint of whole fresh vegetables was 0.36 kg CO₂ eq/kg, whilst for fresh-cut and pre-cooked vegetables it was 0.74 kg CO₂ eq/kg and 0.87 kg CO₂ eq/kg, respectively. The vegetable farming was the main contributor for all the studied vegetables, whole or processed, with the following carbon footprint contributions:

73.4% for whole fresh vegetables, 35.7% for fresh-cut vegetables, and 25.2% for pre-cooked vegetables (Tables SI5 to SI7). The contribution of the vegetable farming stage was lower for the fresh-cut and the pre-cooked vegetables due to the higher impacts during the other life cycle stages and because of the inclusion of auxiliary materials (chlorine and detergent) or the sauces for pre-cooked vegetables (Tables SI6 to SI7). For all vegetables, the fertiliser production and application to crops was the main contributor to almost all environmental impact categories. The irrigation also had a relevant contribution to ionising radiation, marine ecotoxicity and mineral resources scarcity impact categories due to the electricity consumed in the pumping stage. Canaj et al. (2021a) and Martin-Gorriz et al. (2020) also showed that fertilisation and irrigation contributed strongly to the carbon footprint of vegetable products.

For the whole fresh vegetables, the transport to market was the second main contributor to the carbon footprint (23.9%), with relevant impacts on terrestrial ecotoxicity (67.3%) and fossil resource scarcity (37.0%). The third contributor to the carbon footprint was the production of

Table 3 Midpoint impact values for whole fresh, fresh-cut, and pre-cooked vegetables per kg of product at the entrance gate of the market (red for higher impacts and green for lower impacts)

Impact category	Unit	Whole fresh ^a	Fresh-cut	Pre-cooked
Global warming	kg CO ₂ eq	3.63E-01	7.38E-01	8.75E-01
Stratospheric ozone depletion	kg CFC-11 eq	4.27E-06	3.75E-06	4.12E-06
Ionising radiation	kBq Co-60 eq	1.71E-02	2.08E-01	2.70E-01
Ozone formation, Human health	kg NO _x eq	1.50E-03	2.22E-03	2.52E-03
Fine particulate matter formation	kg PM2.5 eq	6.83E-04	1.22E-03	1.36E-03
Ozone formation, Terrestrial ecosystems	kg NO _x eq	1.52E-03	2.26E-03	2.57E-03
Terrestrial acidification	kg SO ₂ eq	3.14E-03	3.49E-03	4.78E-03
Freshwater eutrophication	kg P eq	1.63E-04	5.16E-04	5.67E-04
Marine eutrophication	kg N eq	6.88E-04	7.61E-04	8.58E-04
Terrestrial ecotoxicity	kg 1,4-DCB	2.88E+00	3.74E+00	4.08E+00
Freshwater ecotoxicity	kg 1,4-DCB	9.60E-03	4.94E-02	6.04E-02
Marine ecotoxicity	kg 1,4-DCB	1.35E-02	5.97E-02	6.62E-02
Human carcinogenic toxicity	kg 1,4-DCB	1.46E-02	6.07E-02	6.50E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	7.40E-01	2.04E+00	1.83E+00
Land use	m ² a crop eq	2.56E-01	6.32E-01	7.21E-01
Mineral resource scarcity	kg Cu eq	2.89E-03	8.34E-03	7.54E-03
Fossil resource scarcity	kg oil eq	9.08E-02	2.34E-01	2.51E-01
Water consumption	m ³	1.13E-02	6.06E-02	6.15E-02

^aThe mean environmental impact of potato, aubergine, and broccoli (Supplementary information: Tables SI2-SI4)

packaging materials (6.0%), with notable impacts on land use (25.7%), ionising radiation (14.9%) and fossil resource scarcity (12.8%) due to material extraction and electricity consumption for their production (Table SI5). As processed vegetable production required more resources in their production stage, there was a burden shift. For instance, these types of processed products demand more packaging materials per FU. For the fresh-cut vegetables and the pre-cooked vegetables, it was the second main contributor to the carbon footprint (26.1 to 28.4%), which was also the main contributor to the fossil resource scarcity impact category (45.8 to 50.1%). The third largest contributor to the carbon footprint was the vegetable processing (18.9 to 21.7%), including, cleaning, washing, disinfection, etc., which resulted in the consumption of large amounts of electricity and water. This processing stage also significantly contributed to other environmental categories such as ionising radiation (71.0%) and fossil resource scarcity (18.7 to 26.7%), mainly because of the highest electricity consumption among all life cycle stages. In addition, the production of the fresh-cut and the pre-cooked vegetable processing equipment was the main contributor to the human carcinogen toxicity impact category (66.7 to 70.0%). In contrast to this result, Fusi et al. (2016) found that vegetable processing was the main contributor to the carbon footprint of fresh-cut salads due to the high amount of wastewater generated during vegetable disinfection. The transport of packaged products to the market accounted for 11.1 to 12.9% of the carbon footprint (Tables SI6 and SI7) and was the main factor in the terrestrial ecotoxicity impact (43.5 to 44.2%).

It should be noted that these products demand auxiliary materials, such as chlorine and detergent, or sauces (in the case of pre-cooked vegetables) that increase the impact of transport of materials to the factory (core stage). Despite this impact, auxiliary materials production and their transport had a negligible contribution when it is compared to the total environmental impact. Additionally, it should be noted that the sauces substantially contributed to several impact categories during the upstream stage such as land use (24.0%),

terrestrial acidification (18.7%), freshwater ecotoxicity (16.9%) and the carbon footprint (13.6%). These emissions were related to dairy products to be used for bechamel production and the olive oil production process. On the other hand, it is important to highlight the environmental savings obtained from the vegetable biowaste generated inside the factory; it was used as a substitute for maize in animal feeding. In the whole fresh vegetable industry, biowaste could outweigh the emissions produced in the core stage for all impact categories (Table SI5). Nevertheless, said saving was much higher in the processed vegetables (Tables SI6 to SI7), due to a larger amount of biowaste per FU being generated by the processed vegetables (0.22 to 0.30 kg) compared to the whole fresh vegetables (0.17 kg). However, due to the higher environmental impact of the processing life cycle stage, these savings had a lower contribution. For both types of products (whole fresh and processed vegetables), the packaging waste management also provided savings in most impact categories, due to recycling the materials. More details on the environmental analysis of these food products can be found in the supplementary information.

3.2 Life cycle impact assessment at endpoint level

The quantitative results for human health (DALY), impact on ecosystems (species per year) and resources scarcity (USD_{2013}) of the studied vegetables per FU (1 kg of product at the entrance gate of the market) are shown in Table 4. The damage to human health ranged from $1.01\text{E-}06$ DALY/kg of whole fresh vegetables to $2.49\text{E-}06$ DALY/kg of pre-cooked vegetables. Figure 3 shows the contributions of these damage categories. For all of them, the greatest contribution to human health was obtained in the farming stage (35.8 to 82.3%) (Fig. 3A). This damage was related to fertiliser production and its application to the crops, irrigation, and diesel consumption during farming practices. From the conversion of midpoint to endpoint categories, it can be seen that the damage to human health was mainly due to global

Table 4 Endpoint impact assessment of whole fresh, fresh-cut, and pre-cooked vegetables per kg of product at the entrance gate of the market (red for higher impacts and green for lower impacts)

Damage category	Unit	Whole fresh	Fresh-cut	Pre-cooked
Human health	^a DALY	1.01E-06	2.31E-06	2.49E-06
Ecosystems	^b Species.yr	4.30E-09	9.82E-09	1.13E-08
Resources	^c USD ₂₀₁₃	3.03E-02	8.54E-02	9.05E-02

^aDALY (disability adjusted life years): Years that a given person loses or is incapacitated due to illness or accident

^bSpecies.yr: This describes the local species loss integrated over time

^cUSD₂₀₁₃: The extra costs involved for future mineral and fossil resource extraction

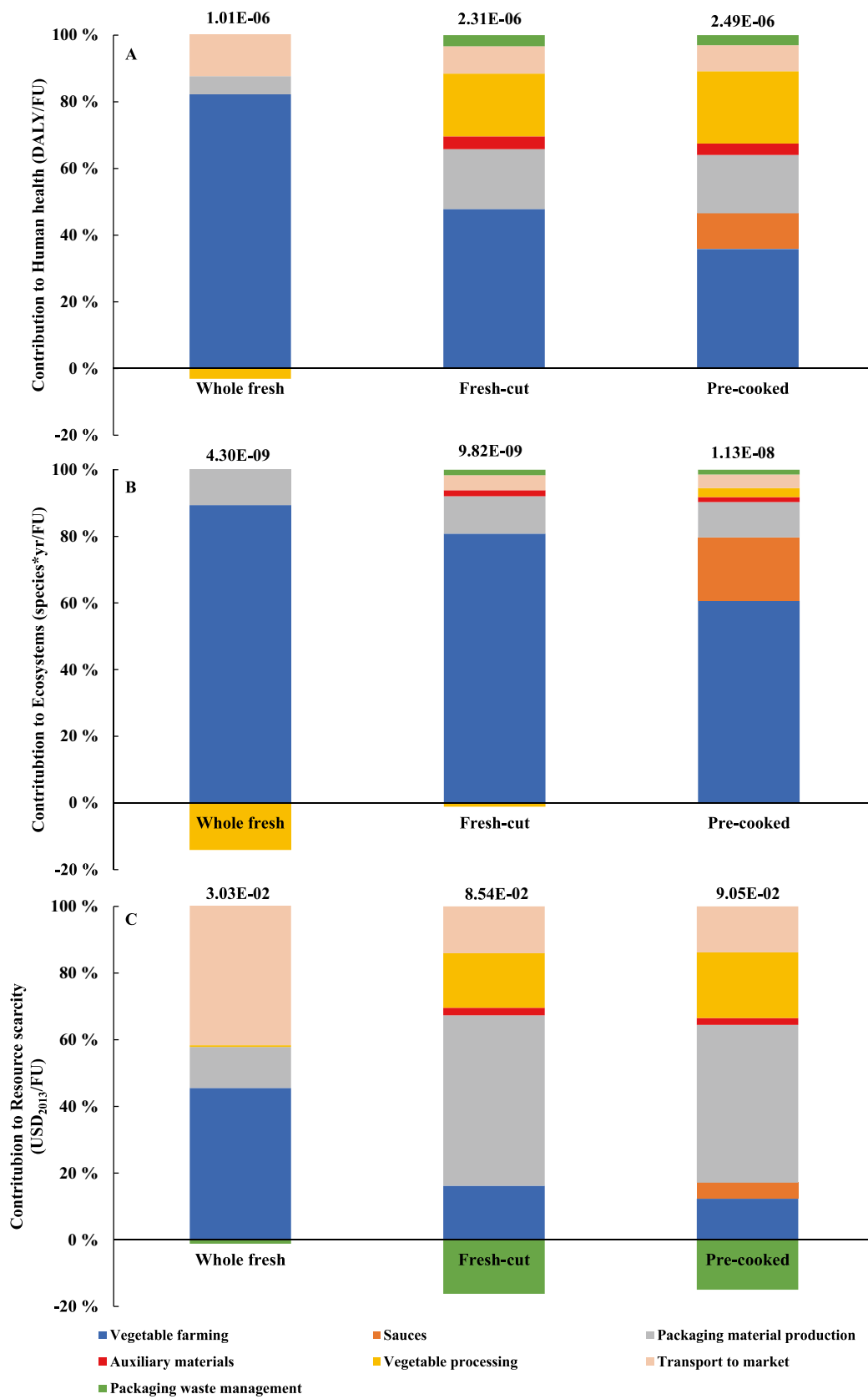


Fig. 3 Endpoint impact values and contribution of main processes for whole fresh, fresh-cut, and pre-cooked vegetables production to human health (A), ecosystems (B) and resources scarcity (C) impact categories

warming and fine particulate matter formation impact categories (Table SI8), as Canaj et al. (2020) identified for tomato cultivation. Kumar et al. (2023), who evaluated the environmental impact of conventional potato cultivation, found that fertilisation and irrigation played a significant role in the human health and ecosystems categories, due to the use of chemical fertilisers and pesticides.

Ecosystem impacts ranged from 4.30E-09 species per year/kg of whole fresh vegetable to 1.13E-08 species per year/kg of pre-cooked vegetables (Table 4). The land use and global warming (terrestrial ecosystems) and terrestrial acidification categories were particularly important for this damage (Table SI8). In this instance, it was the consequence of land occupation for agricultural purposes and its transformation due to agricultural activity, since the farming stage (60.7% to 89.4%) was the highest contributor to this damage (Fig. 3B) in all cases. Canaj et al. (2020) obtained lower ecosystem damage for tomato farming (cradle to farm gate) of 7.68E-10 to 1.01E-09 species per year/kg and identified the impact categories relevant to ecosystem damage as being land use, water consumption (terrestrial ecosystems), global warming, and terrestrial acidification. Similarly, Crenna et al. (2019) calculated the Potentially Disappeared Fraction (PDF) of species over time (PDF per years) of the European diet (from cradle to grave). For example, that work found 4.13 PDF per year/kg of potato and 28.53 PDF per year/kg of meat-based pre-cooked meal. For both products, the categories that contributed most to the loss of species richness were global warming, land use, and acidification, but across food products, the impact category highlighted as having the greatest contribution to ecosystem quality was land use. This fact was also reported in the literature: the ReCiPe 2016 methodology highlights the land use and global warming categories as the indicators causing the greatest damage to ecosystem quality and biodiversity (MEA 2005; Barnosky et al. 2011).

Resource scarcity (USD₂₀₁₃) represents the extra costs of future extraction of mineral and fossil resources. The damage costs associated with this category ranged from 3.03E-02 to 9.05E-02, with the highest values being for the processed vegetables products. For all products, these costs were mainly associated with the fossil resource scarcity category (Table SI8). In this study, the stage with the largest contribution depended on the product type (Fig. 3C). For whole fresh vegetables, the main contributors were vegetable farming (45.5%), due to nitrogen fertiliser production and the amount of diesel used in that stage, and the transport stage (42.8%) due to fossil fuel consumption, as also reported by Pedreschi et al. (2022). Ordikhani et al. (2021) and Mostashari-Rad et al. (2021) identified the same factors as being the main drivers of resource scarcity in horticultural crops production. On the other hand, for the fresh-cut and pre-cooked vegetables, the packaging materials production

(47.3–51.1%) was the main factor, mainly due to obtaining the raw plastic material.

3.3 Assessment of damage costs: the monetised LCA impacts

3.3.1 Monetisation endpoint damage cost obtained from midpoint and endpoint levels

The results of the damage costs and their contribution based on the midpoint categories are shown in Fig. 4. The damage costs for whole fresh vegetables were 0.16 €/kg. For fresh-cut and pre-cooked vegetables the damage costs were 0.38 and 0.42 €/kg, respectively, as these processed products had the greatest environmental impact in most of the impact categories evaluated (Table 3). For all products, the largest share of the damage cost came from fossil resource scarcity (22.6–25.0%), global warming (20.1–21.6%), fine particulate matter (15.0–19.6%) and land use (16.3–17.9%). The damage cost of whole fresh vegetables was obtained from only three crops out of ten included in the fresh-cut and pre-cooked vegetables. The damage cost of the remaining single crops from cradle to market could range from 0.10 €/kg to 0.23 €/kg (Fig. SI1). Nevertheless, the impact categories that contributed most differed since they depended on the agricultural practices used. According to the Agribalyse 3.0.1 database (Asselin-Balençon et al. 2020), broccoli farming has a higher consumption of mineral fertilisers, energy for irrigation and diesel for field operations (Table SI1). Moreover, the higher land use demand for potato cultivation was noteworthy and was the highest contributor to its damage cost (Fig. SI1).

Overall, based on the environmental midpoint evaluation, vegetable farming was the main contributor to this damage cost, due to nitrogen fertiliser production and the energy consumption for irrigation. In addition, the damage cost obtained for the fossil resource scarcity impact category of the fresh-cut and pre-cooked vegetables came from packaging production.

The results of the damage costs based on damage categories and their contribution are shown in Fig. 5. The differences in damage costs obtained from the monetization of the midpoint and endpoint impact categories were marginal, primarily because only results obtained with endpoint monetization factors are presented. The damage cost for whole fresh vegetables was 0.15 €/kg, while the processed vegetables ranged from 0.36 to 0.40 €/kg. The damage to human health was the main contributor for all products analysed, ranging from 47.1% for pre-cooked to 49.9% for whole fresh vegetables. That damage was dominated by global warming-human health, fine particulate matter formation and human non-carcinogenic toxicity categories (Table SI8).

The ecosystems impact category was the second highest contributor, ranging from 32.6% for fresh-cut to 34.1%

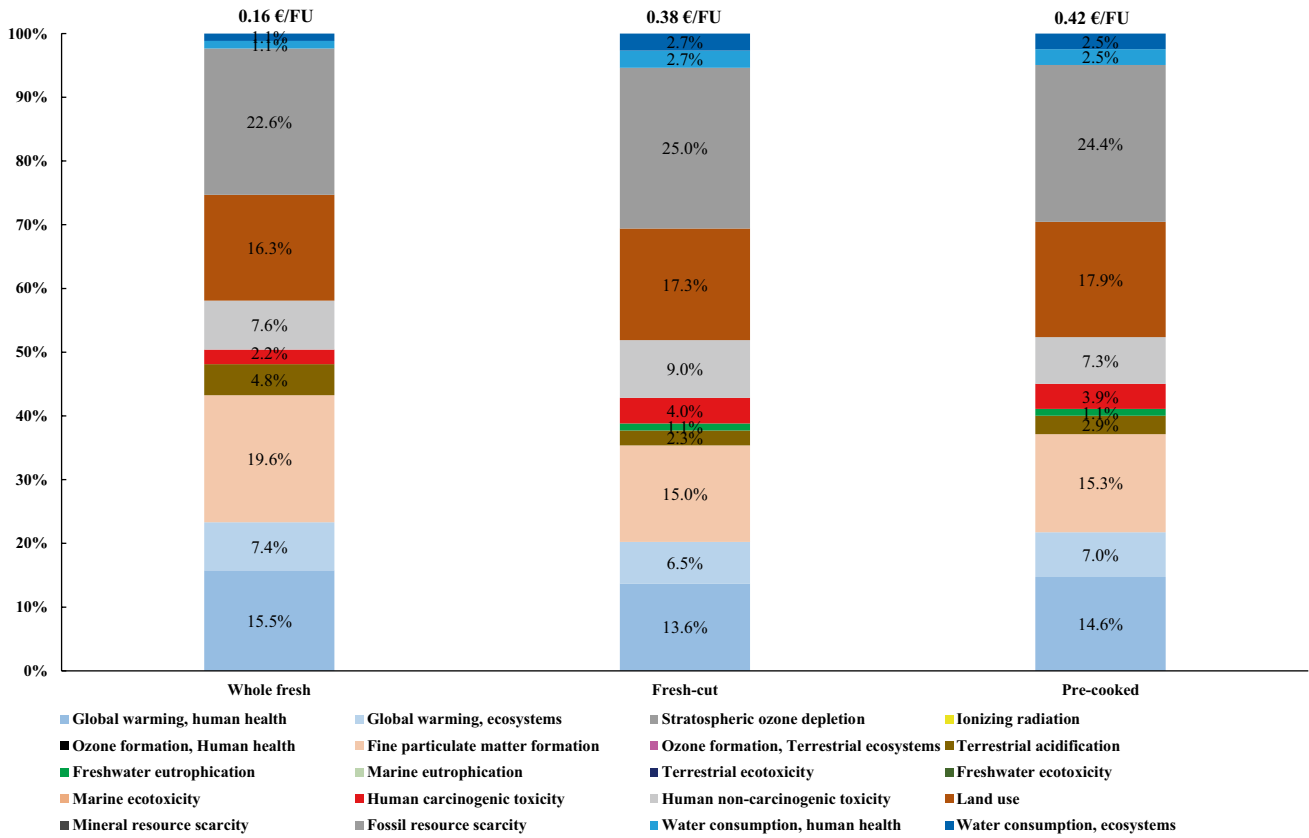


Fig. 4 Endpoint damage cost values and damage cost contributions for whole fresh, fresh-cut, and pre-cooked vegetables based on midpoint impact categories

for pre-cooked vegetables. Likewise, based on the endpoint evaluation, the damage cost on human health and ecosystems categories was caused mainly by agricultural production,

due to mineral fertiliser production, energy consumed for irrigation, and diesel combustion in agricultural operations (transport of inputs and harvesting). The damage cost was

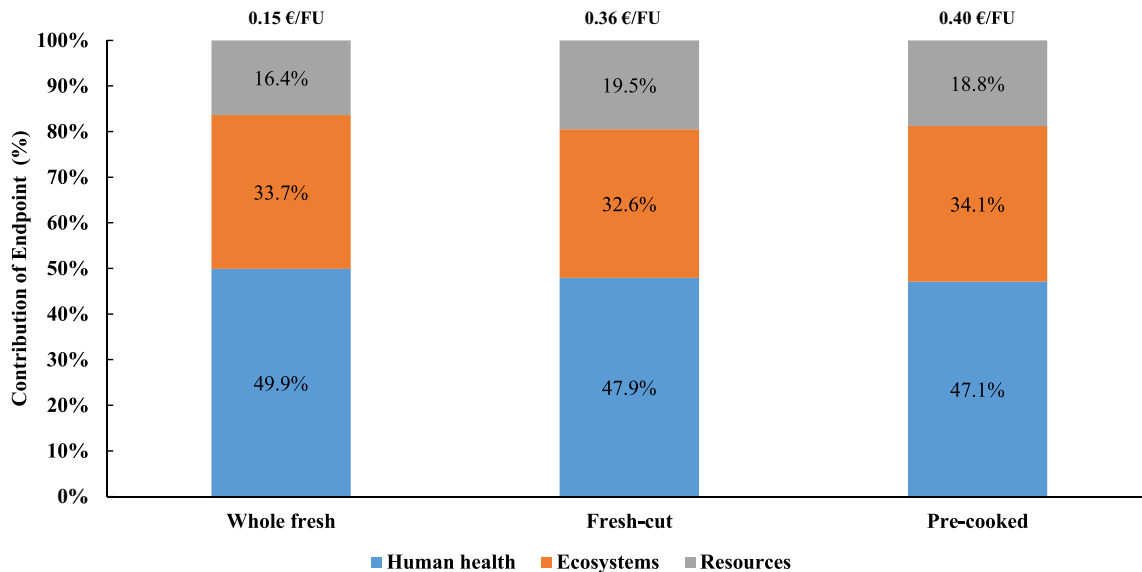


Fig. 5 Damage cost values and contribution of damage costs of whole fresh, fresh-cut, and pre-cooked vegetables based on endpoint impact categories

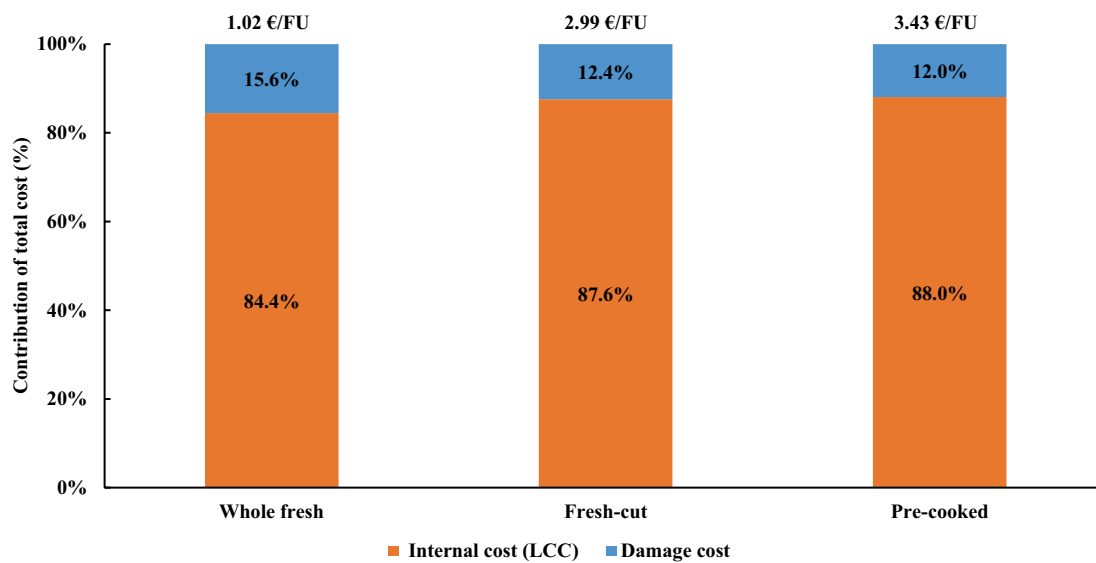


Fig. 6 Total costs and contribution of internal cost and damage cost for whole fresh, fresh-cut, and pre-cooked vegetables

mainly dominated by human health (Fig. 5) Furthermore, Arendt et al. (2020) found that monetisation factors were more developed for human health than resources or ecosystem. This may explain why the damage costs were higher in this category. Regarding the resources damage cost, it was principally caused by the transport stage (from factory to entrance to the market) for whole fresh vegetables, whilst for processed vegetables it was principally caused by packaging production.

The results obtained for agriculture production confirm the findings obtained by Hendriks et al. (2023) and Wagner et al. (2022), who both determined that the highest environmental costs of food production and miscanthus cultivation were global warming, land use, and fine particulate matter formation. Likewise, Canaj et al. (2021a) reported that the processes contributing most to the damage costs for fruit and vegetable production were electricity used for irrigation, and fertilisation, which contributed to increases in the global warming, particulate matter formation, acidification and fossil resource scarcity impact categories.

3.3.2 Total cost accounting: aggregation of environmental internal and damage costs

Since the damage costs based on endpoint factors at midpoint and endpoint level were largely the same (Fig. SI4), Fig. 6 shows the average damage cost (from midpoint and endpoint level) and internal costs for the production of 1 kg of whole fresh, fresh-cut, and pre-cooked vegetables. Thus, the total costs for the average of whole fresh vegetables were 1.02 €/kg, while for fresh-cut and pre-cooked vegetables they were 2.99 €/kg and 3.43 €/kg, respectively. The contribution of the damage to the total cost was: 12.0% for

the pre-cooked products, 12.4% for the fresh-cut, and 15.6% for the whole fresh vegetables. Nevertheless, it should be noted that these shares were dependent on the internal costs obtained for each product. Even though the obtained damage cost was the highest for the processed vegetables, the contribution of those damage costs was lower because of the higher internal costs of pre-cooked and fresh-cut vegetables.

4 Conclusions

The present research has determined the total cost of whole fresh and processed vegetables (fresh-cut and pre-cooked) at the market entrance gate. The damage cost was obtained through monetising the environmental impact of these products. Then, the total costs were obtained by adding the damage costs to the internal costs which have been calculated by LCC. Furthermore, this research was conducted to identify the impact categories that contributed most to this damage cost. It should be noted that all vegetables were grown in open field and followed similar cultivation practices. Because of the different degrees of processing (e.g. washing, and pre-cooking and the addition of a sauce for pre-cooked vegetables), the results for the three vegetable groups cannot be compared.

The damage costs were 0.16 €/kg, 0.36 €/kg and 0.41 €/kg for the whole fresh, fresh-cut and the pre-cooked vegetables. The higher damage costs of processed vegetables were due to the higher consumption of electricity for their manufacture (cutting, and/or peeling and/or cleaning, disinfecting and centrifugating). Additionally, pre-cooked included sauces and heating treatment. The damage cost of whole fresh vegetables was caused mainly by fertilisers production

and application, and electricity demand for water pumping. The total costs for the average of the whole fresh vegetables were 1.02 €/kg, while for the fresh-cut and pre-cooked vegetables they were 2.99 €/kg and 3.43 €/kg, respectively.

The impact categories that mainly caused these damage costs were fossil resource scarcity, particulate matter, global warming, and land use. The main contributor to the damage costs in the fossil resource scarcity and particulate matter categories was the transport stage of whole fresh products from industry to supermarket entrance. For processed fresh-cut and pre-cooked vegetables, the damage costs on fossil resource scarcity were mainly caused by raw plastic materials for packaging production. On the other hand, for all products, agricultural production was the main driver of damage costs produced in the global warming and land use impact categories, with that stage being the main contributor to the environmental impact.

In summary, this research highlights the importance of including damage costs in LCC of whole fresh, fresh-cut, and pre-cooked vegetable products. To reduce the damage cost of the assessed products, the following can be recommended mainly focused on three main stages. Firstly, in the vegetable production, it is important to explore the use of sustainable fertilisers that demand fewer resources during their production and have a lower release during their use. Additionally, responsible use of water can be achieved by implementing sensors to estimate crop water needs more efficiently. Regarding the packaging of processed products (fresh-cut and pre-cooked vegetables), it should be eco-designed, with the aim of reducing the plastic consumption and therefore reducing the damage on fossil resource scarcity. Secondly, the processed vegetables industry should move towards a cleaner electricity grid, for instance by installing photovoltaic panels and thus reducing electricity consumption. Finally, to minimise the impact of the distribution stage from factory to market, it is suggested to use trucks that run on cleaner fuels (natural gas, biofuels, electricity, or H₂).

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Author contribution Laura Rasines: Experiments, Data curation, Methodology, Software, Investigation, Writing – original draft preparation. Serni Morera: Experiments, Data curation, Methodology, Investigation, Writing – original draft preparation. Guillermo San Miguel: Conceptualisation, Methodology, Supervision, Validation, Investigation, Writing - review & editing. Encarna Aguayo: Conceptualisation, Supervision, Data curation, Validation, Investigation, Writing - review & editing, Funding acquisition, Project administration.

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Data availability Data will be made available on request.

Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Amadei AM, De Laurentiis V, Sala S (2021) A review of monetary valuation in life cycle assessment: State of the art and future needs. *J Clean Prod* 329:129668. <https://doi.org/10.1016/j.jclepro.2021.129668>
- Arendt R, Bachmann TM, Motoshita M et al (2020) Comparison of different monetization methods in LCA: A review. *Sustainability* 12:1–39. <https://doi.org/10.3390/su122410493>
- Asselin-Balençon A, Broekema R, Teulon H et al (2020) AGRIBALYSE V 3.0: the French agricultural and food LCI database. Methodology for the food products. Ed. ADEME 2020
- Barnosky AD, Matzke N, Tomiya S et al (2011) Has the Earth’s sixth mass extinction already arrived? *Nature* 471:51–57. <https://doi.org/10.1038/nature09678>
- CAMBIOEURO (2023) Cambio Euro Dólar 2013. <https://www.cambioeuro.es/cambio-historico-dolar-2013>. Accessed 5 Feb 2023
- Canaj K, Mehmeti A, Berbel J (2021a) The economics of fruit and vegetable production irrigated with reclaimed water incorporating the hidden costs of life cycle environmental impacts. *Resources* 10:90. <https://doi.org/10.3390/resources10090090>
- Canaj K, Mehmeti A, Cantore V, Todorovi M (2020) LCA of tomato greenhouse production using spatially differentiated life cycle impact assessment indicators: an Albanian case study. *Environ Sci Pollut Res* 27:6960–6970. <https://doi.org/10.1007/s11356-019-07191-7>
- Canaj K, Mehmeti A, Morrone D et al (2021b) Life cycle-based evaluation of environmental impacts and external costs of treated wastewater reuse for irrigation: A case study in southern Italy. *J Clean Prod* 293:126142. <https://doi.org/10.1016/j.jclepro.2021.126142>
- Cerutti AK, Beccaro GL, Bruun S et al (2014) Life cycle assessment application in the fruit sector: State of the art and recommendations for environmental declarations of fruit products. *J Clean Prod* 73:125–135. <https://doi.org/10.1016/j.jclepro.2013.09.017>

- Clune S, Crossin E, Verghese K (2017) Systematic review of greenhouse gas emissions for different fresh food categories. *J Clean Prod* 140:766–783. <https://doi.org/10.1016/j.jclepro.2016.04.082>
- Crenna E, Sinkko T, Sala S (2019) Biodiversity impacts due to food consumption in Europe. *J Clean Prod* 227:378–391. <https://doi.org/10.1016/j.jclepro.2019.04.054>
- Dascălu C, Caraiani C, Gușe R et al (2009) Full cost accounting and social environmental effects on global warming phenomenon. *Account Manag Inf Syst* 8:567–588. <https://doi.org/10.1108/ijaim.2010.36618aad.021>
- Ecoinvent (2021) Ecoinvent database v3.8. Zurich. <https://support.ecoinvent.org/ecoinvent-version-3.8>. Accessed 1 Dec 2023
- EEA (2022) Rethinking agriculture. In: *Matern Child Nutr*. <https://www.eea.europa.eu/publications/rethinking-agriculture>. Accessed 22 Nov 2023
- EPD System (2019a) Product Category Rule (PCR): UN CPC 213, 214. Prepared and preserved vegetable and fruit products, including juice. 33. <https://www.environdec.com/pcr-library>. Accessed 14 Nov 2023
- EPD System (2019b) Product Category Rule (PCR): UN CPC multiple. Packaging. 39 <https://environdec.com/pcr-library/with-documents>. Accessed 21 Nov 2023
- EPD System (2020) Product Category Rule (PCR): UN CPC 011, 012, 014, 017, 0191. Arable and Vegetable Crops. 29. <https://environdec.com/pcr-library/with-documents>. Accessed 14 Nov 2023
- European Commission (2020) Final Report Summary: Energy costs, taxes and the impact of government interventions on investments. Rotterdam, p 90. ISBN 978-92-76-23124-0
- Fusi A, Castellani V, Bacenetti J et al (2016) The environmental impact of the production of fresh cut salad: a case study in Italy. *Int J Life Cycle Assess* 21:162–175. <https://doi.org/10.1007/s11367-015-1019-z>
- Giovenzana V, Casson A, Beghi R et al (2021) Evaluation of consumer domestic habits on the environmental impact of ready-to-eat and minimally processed fresh-cut lamb's lettuce. *Sustain Prod Consum* 28:925–935. <https://doi.org/10.1016/j.spc.2021.07.021>
- Halkier B (2017) Normalising convenience food? *Food, Cult Soc* 20:133–151. <https://doi.org/10.1080/15528014.2016.1243768>
- Hendriks S, de Groot Ruiz A, Herrero Acosta M et al (2023) The true cost of food: a preliminary assessment. In: von Braun J, Afsana K, Fresco LO, Ali Hassan MH (eds) *Science and innovations for food systems transformation*. Springer, Switzerland, pp 581–601. <https://doi.org/10.1007/978-3-031-15703-5>
- Hoek AC, Malekpour S, Raven R et al (2021) Towards environmentally sustainable food systems: decision-making factors in sustainable food production and consumption. *Sustain Prod Consum* 26:610–626. <https://doi.org/10.1016/j.spc.2020.12.009>
- Hoogmartens R, Van PS, Van AK, Dubois M (2014) Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. *Environ Impact Assess Rev* 48:27–33. <https://doi.org/10.1016/j.eiar.2014.05.001>
- Huijbregts MA, Steinmann ZJ, Elshout PM et al (2016) ReCiPe 2016 v1.1. A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization. RIVM Report 2006-0104a. National Institute for Public Health and the Environment, Bilthoven. <https://www.rivm.nl/bibliotheek/rapporten/2016-0104.html>
- Huijbregts MAJ, Steinmann ZJN, Elshout PMF et al (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int J Life Cycle Assess* 22:138–147. <https://doi.org/10.1007/s11367-016-1246-y>
- INE (2022) Instituto Nacional de Estadística (INE). Cálculo de variaciones del Índice de Precios de Consumo. <https://www.ine.es/varipc>. Accessed 19 Dec 2022
- Isacs L, Finnveden G, Dahllöf L et al (2016) Choosing a monetary value of greenhouse gases in assessment tools: A comprehensive review. *J Cleaner Prod* 127:37–48. <https://doi.org/10.1016/j.jclepro.2016.03.163>
- ISO (2006a) ISO 14040:2006. Environmental management. Life cycle assessment. Principles and framework. Bruxelles. <https://www.iso.org/standard/37456.html>. Accessed 10 Oct 2020
- ISO (2006b) ISO 14044:2006 Environmental management. Life cycle assessment. Requirements and guidelines. Bruxelles. <https://www.iso.org/standard/38498.html>. Accessed 10 Oct 2020
- ISO (2019a) ISO 14008:2019. Monetary valuation of environmental impact and related environmental aspects. <https://www.iso.org/standard/43243.html>. Accessed 26 Sep 2023
- ISO (2019b) ISO 14007:2019 Environmental management. Guidelines for determining environmental cost and benefits. <https://www.iso.org/standard/70139.html>. Accessed 26 Sep 2023
- ISO (2023) ISO 14054:2023 Natural Capital Accounting for Organizations. <https://www.iso.org/standard/43270.html>. Accessed 26 Sep 2023
- Keng ZX, Chong S, Ng CG et al (2020) Community-scale composting for food waste: A life-cycle assessment-supported case study. *J Clean Prod* 261:121220. <https://doi.org/10.1016/j.jclepro.2020.121220>
- Kumar R, Bhardwaj A, Singh LP, Singh G (2023) Quantifying ecological impacts: A comparative life cycle assessment of conventional and organic potato cultivation. *Ecol Modell* 486:110510. <https://doi.org/10.1016/j.ecolmodel.2023.110510>
- MAPA (2022a) Ministerio de Agricultura, Pesca y Alimentación (MAPA). Registro de productos fitosanitarios. <https://www.mapa.gob.es/es/agricultura/temas/sanidad-vegetal/productos-fitosanitarios/fitos.asp>. Accessed 21 Nov 2023
- MAPA (2022b) Ministerio de Agricultura, Pesca y Alimentación (MAPA). Boletín semanal de precios de Frutas y Hortalizas. https://www.mapa.gob.es/es/agricultura/temas/producciones-agricolas/frutas-y-hortalizas/boletines_2022.aspx. Accessed 24 Dec 2022
- Martin-Gorriz B, Gallego-Elvira B, Martínez-Alvarez V, Maestre-Valero JF (2020) Life cycle assessment of fruit and vegetable production in the Region of Murcia (south-east Spain) and evaluation of impact mitigation practices. *J Clean Prod* 265:121656. <https://doi.org/10.1016/j.jclepro.2020.121656>
- MEA (2005) Ecosystems and human well-being: Opportunities and challenges for business and industry. World Resources Institute, Washington, DC
- MITECO (2019). Ministerio para la Transición Ecológica y el Reto Demográfico (MITECO). Memoria anual de generación de residuos: Generación y gestión de residuos de envases en España, 2019. https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/publicaciones/tabladatosenvasesyresiduosdeenvasos2019_tcm30-529105.pdf. Accessed 7 Nov 2020
- Morel S, Traverso M, Preiss P (2018) Discussion panel—assessment of externalities: monetisation and social LCA. In: Benetto E, Guiton M, Gericke K (eds) *Designing sustainable technologies, products and policies. From science to innovation*. Springer, Switzerland, pp 391–396. <https://doi.org/10.1007/978-3-319-66981-6>
- Mostashari-Rad F, Ghasemi-Mobtaker H, Taki M, Nabavi-Pelesaraei A (2021) Exergoenvironmental damages assessment of horticultural crops using ReCiPe2016 and cumulative exergy demand frameworks. *J Clean Prod* 278:123788. <https://doi.org/10.1016/j.jclepro.2020.123788>
- Notarnicola B, Tassielli G, Renzulli PA et al (2017) Environmental impacts of food consumption in Europe. *J Clean Prod* 140:753–765. <https://doi.org/10.1016/j.jclepro.2016.06.080>
- Ordikhani H, Parashkoohi MG, Zamani DM, Ghahderijani M (2021) Energy-environmental life cycle assessment and cumulative exergy demand analysis for horticultural crops (Case study:

- Qazvin province). *Energy Rep* 7:2899–2915. <https://doi.org/10.1016/j.egy.2021.05.022>
- Parajuli R, Thoma G, Matlock MD (2019) Environmental sustainability of fruit and vegetable production supply chains in the face of climate change: A review. *Sci Total Environ* 650:2863–2879. <https://doi.org/10.1016/j.scitotenv.2018.10.019>
- Pedreschi R, Ponce E, Hernández I et al (2022) Short vs. long-distance avocado supply chains: Life cycle assessment impact associated to transport and effect of fruit origin and supply conditions chain on primary and secondary metabolites. *Foods* 11:1807. <https://doi.org/10.3390/foods11121807>
- Pizzol M, Weidema B, Brandão M, Osset P (2015) Monetary valuation in life cycle assessment: A review. *J Clean Prod* 86:170–179. <https://doi.org/10.1016/j.jclepro.2014.08.007>
- Ponsioen T, Nuhoff-isakhanyan G, Vellinga T et al (2020) Monetisation of sustainability impacts of food production and consumption. Wageningen Economic Research, Wageningen, p 24. <https://doi.org/10.18174/522812> (Report 2020-010)
- Poore J, Nemecek T (2018) Reducing food's environmental impacts through producers and consumers. *Science* 360(80-):987–992. <https://doi.org/10.1126/science.aag0216>
- PRé Consultant (2022) SimaPro v 9.3. The Netherlands
- Rasines L, Morera S, San Miguel G et al (2023) Environmental and economic sustainability of fresh-cut and pre-cooked vegetables. *Sci Total Environ* 872:162169. <https://doi.org/10.1016/j.scitotenv.2023.162169>
- San Miguel G, Ruiz D (2021) Environmental sustainability of a pork and bean stew. *Sci Total Environ* 798:149203. <https://doi.org/10.1016/j.scitotenv.2021.149203>
- Saxe H, Jensen JD, Bølling Laugesen SM, Bredie WLP (2019) Environmental impact of meal service catering for dependent senior citizens in Danish municipalities. *Int J Life Cycle Assess* 24:654–666. <https://doi.org/10.1007/s11367-018-1487-z>
- Schmidt Rivera XC, Azapagic A (2019) Life cycle environmental impacts of ready-made meals considering different cuisines and recipes. *Sci Total Environ* 660:1168–1181. <https://doi.org/10.1016/j.scitotenv.2019.01.069>
- Schmidt Rivera XC, Azapagic A (2016) Life cycle costs and environmental impacts of production and consumption of ready and home-made meals. *J Clean Prod* 112:214–228. <https://doi.org/10.1016/j.jclepro.2015.07.111>
- Sieti N, Schmidt Rivera XC, Stamford L, Azapagic A (2019) Environmental sustainability assessment of ready-made baby foods: Meals, menus and diets. *Sci Total Environ* 689:899–911. <https://doi.org/10.1016/j.scitotenv.2019.06.363>
- Trolle E, Nordman M, Lassen AD et al (2022) Carbon footprint reduction by transitioning to a diet consistent with the danish climate-friendly dietary guidelines: a comparison of different carbon footprint databases. *Foods* 11:1119. <https://doi.org/10.3390/foods11081119>
- UNE-EN (2012) UNE-EN 15084 +A2:2020/AC. Sustainability of construction works. Environmental product declarations. Core rules for product category of construction products. <https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=norma-une-en-15084-2012-a2-2020-n0063508>. Accessed 17 Feb 2022
- United Nations (2023) OECD glossary: damage cost. <https://archive.unescwa.org/sd-glossary/damage-cost>. Accessed 21 Dec 2023
- USDA (2021) United States Department of Agriculture, Agriculture Research Service. FoodData Central. <https://fdc.nal.usda.gov/index.html>. Accessed 1 Oct 2021
- Vigil M, Laza MP, Moran-Palacios H, Cabal JVA (2020) Optimizing the environmental profile of fresh-cut produce: Life cycle assessment of novel decontamination and sanitation techniques. *Sustainability* 12:3674. <https://doi.org/10.3390/su12093674>
- Wagner M, Winkler B, Lask J et al (2022) The true costs and benefits of miscanthus cultivation. *Agronomy* 12:3071. <https://doi.org/10.3390/agronomy12123071>
- Weidema BP (2009) Using the budget constraint to monetarise impact assessment results. *Ecol Econ* 68:1591–1598. <https://doi.org/10.1016/j.ecolecon.2008.01.019>
- Willett W, Rockström J, Loken B et al (2019) Food in the anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. *Lancet* 393:447–492. [https://doi.org/10.1016/S0140-6736\(18\)31788-4](https://doi.org/10.1016/S0140-6736(18)31788-4)
- Wolfson JA, Bleich SN, Smith KC, Frattaroli S (2016) What does cooking mean to you?: Perceptions of cooking and factors related to cooking behavior. *Appetite* 97:146–154. <https://doi.org/10.1016/j.appet.2015.11.030>
- Zampori L, Pant R (2019) Suggestions for updating the Product Environmental Footprint (PEF) method. Publications Office of the European Union, Luxembourg. <https://doi.org/10.2760/424613> (EUR 29682 EN, ISBN 978-92-76-00654-1, JRC115959)

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