Science of the Total Environment xxx (xxxx) xxx

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Optimizing the environmental sustainability of alternative post-harvest scenarios for fresh vegetables: A case study in Spain

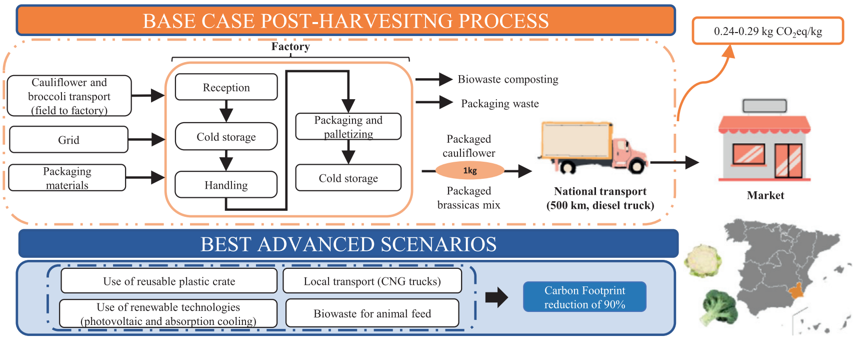
Laura Rasines [a,b], Guillermo San Miguel [c], Ángel Molina-García [d], Francisco Artés-Hernández [a,b], Eloy Hontoria [e], Encarna Aguayo [a,b,*]

[a] *Postharvest and Refrigeration Group, Universidad Politécnica de Cartagena (UPCT), 30202 Cartagena, Spain*
[b] *Food Quality and Health Group, Institute of Plant Biotechnology (UPCT), Campus Muralla del Mar, 30202, Cartagena, Spain*
[c] *School of Industrial Engineering (ETSII), Grupo de Agroenergética, Universidad Politécnica de Madrid (UPM), 28006, Madrid, Spain*
[d] *Department of Automatics, Electrical Engineering and Electronic Technology, UPCT, Spain*
[e] *Department of Business Economics, UPCT, Spain*

HIGHLIGHTS

- Post-harvest Carbon footprint (CF) ranged between 0.24 and 0.29 kg CO_2 eq/kg.
- Packaging material production was the main contributor of the post-harvest.
- Reusable plastic crate reduced the environmental impact from 65.3 to 84.5 %.
- Renewable technologies in the processing factory reduced the CF by 67 %.
- The CF of transport improved with compressed natural gas and hybrid trucks.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Kuishuang Feng

Keywords:
Life cycle assessment
Agriculture
Packaging
Broccoli
Postharvest
Reusable plastic crates (RPCs)

ABSTRACT

The aim of this research is to define different scenarios that optimize the environmental sustainability of the post-harvest stage of vegetable products (cauliflower and brassicas mix). These scenarios considered different packaging materials; energy generation technologies for the processing plant (standard electricity mix vs. renewable options); organic waste management (composting, anaerobic digestion, and animal feeding); and refrigerated transportation (local, national, and international, using diesel, natural gas, and hybrid trucks and railway). The analysis has been carried out based on a foreground inventory provided by a company that operating internationally, in accordance with the International Organization for Standardization (ISO) 14,040 methodological framework and following the latest Product Environmental Footprint (PEF) protocols. The analysis describes four midpoint categories, single score (SS) using EF3.0 life cycle impact assessment (LCIA) methodology and the Cumulative Energy Demand. The carbon footprint (CF) of the post-harvest stage for a base case scenario ranged between 0.24 and 0.29 kg CO_2 eq/kg of vegetable, with a strong contribution associated to the production of packaging materials (57.8–65.2 %) and the transport stage (national range in conventional diesel vehicles) (31.5–38.0 %). Comparatively, lower emissions were associated with the energy consumed at the processing factory (up to 4.1 %) while the composting of organic waste management produced some impact savings (up to −3.5 %). Although certain differences were observed, the dominance of the transport stage and the packaging materials is sustained in all the other environmental impact and energy categories evaluated. The most effective measures to reduce the environmental footprint of the post-harvest stage involve: i) using reusable packaging materials; ii) reducing the transport range and using vehicles running on natural gas or

---

* Corresponding author at: Postharvest and Refrigeration Group, Universidad Politécnica de Cartagena (UPCT), 30202 Cartagena, Spain.
E-mail address: encarna.aguayo@upct.es (E. Aguayo).

http://dx.doi.org/10.1016/j.scitotenv.2022.160422
Received 27 March 2022; Received in revised form 28 September 2022; Accepted 18 November 2022

Please cite this article as: L. Rasines, G.S. Miguel, Á. Molina-García, et al., Optimizing the environmental sustainability of alternative post-harvest scenario..., Science of the Total Environment, http://dx.doi.org/10.1016/j.scitotenv.2022.160422

hybrid technologies; iii) the incorporation of renewable energy to supply the factory; and iv) the utilization of the organic residues in higher value applications such as animal feeding. Implementing the measures proposed in this study would reduce the post-harvest CF of fresh vegetables by 90 %.

1. Introduction

About 21–37 % of all anthropogenic greenhouse gas (GHG) emissions are associated with food systems. These do not only arise from the agricultural activities needed to produce food commodities (9–14 %), but also derive from land use and land-use changes (LULUC) (5–14 %) and other activities that take place downstream of the agricultural stage to complete the food supply chain (5–10 %) (e.g., food storage and cooling, transport, packaging, processing, retailing, and final use) (Mbow et al., 2019). A continued increase in the environmental pressure exerted by food and agricultural systems is expected in the coming years as the Food and Agriculture Organization (FAO) estimates a 50 % increase in food production by 2050 due to a growing population and global dietary improvements (FAO, 2018). Spain is the largest producer of fresh fruit and vegetables in the European market with over 28 Mt. in 2020 (MAPA, 2021a) The Region of Murcia, in south-eastern Spain, is the leading producer of cauliflower (31,146 t/year) and broccoli (206,600 t/year), representing 13.2 % and 36.5 % of the total national output, respectively, and occupying over 13,750 ha of agricultural land (MAPA, 2021b).

In a global situation marked by the climate crisis and the degradation of natural ecosystems, process-based life cycle assessment (LCA) has been postulated as a particularly useful tool for evaluating the environmental performance of consumer products and services. This applies to agricultural systems, which have been extensively studied following the standardized framework of the International Organization for Standardization (ISO) 14040:2006 (ISO, 2006a). Most of those studies focus on the production phase (pre-harvest), and have been published in the form of scientific papers, Environmental Product Declarations (EPD) and in background Life Cycle Inventory (LCI) databases specialized in food and agriculture products, such as Agribalyse (Colomb et al., 2014), Agri-footprint (Durlinger et al., 2014), Quantis World Food LCA Database (WFLDB) (Bengoa et al., 2019), and ESU World Food LCA Database (ESU Services, 2021). Regarding the pre-harvest stage of the vegetables considered in this study (cauliflower and broccoli), the scientific literature describes Carbon Footprint values (CF) ranging from nearly zero (0.01 kg CO_2 eq/kg) (Romero-Gámez et al., 2014) for scenarios characterized by minimal human contribution, up to 0.25 kg CO_2 eq/kg (Bartzas et al., 2015; Maraseni et al., 2012; Martin-Gorriz et al., 2020, 2014; Pereira et al., 2021; Persiani et al., 2019). The differences reported are associated primarily with differences in the irrigation process regarding water source (rain, river, well), abstraction technology (gravity, mechanical, electric pumping, etc.) and irrigation technology (sprinkler, drip, etc.), cultivation system (open-field, greenhouse, hydroponic, rotation crops, intercropping, etc.), fertilization requirements, degree of mechanization and production yields.

Less scientific effort has been dedicated to assessing the environmental performance of processes downstream of this agricultural stage, although its contribution to the value chain of food systems is by no means negligible. These post-harvest processes include handling (sorting and/or sizing) and processing, packaging, storage, cooling and transport to the final consumer, including the management of organic residues and packaging components at the end of their useful life (Boschiero et al., 2019). Table 1 describes selected publications which have calculated the LCA or CF of different fruit and vegetables throughout their value chain under different impact assessment methods, where “cradle-to-market” considers the delivery of the products to the retailer as a downstream boundary, and “cradle-to-grave” also incorporates the impacts generated by the end consumer. This table compiles the CF of these products standardized for the same functional unit (1 kg) and the contributions per main stages. Liu et al. (2010) reported minimal carbon emissions (0.06 kg CO_2 eq/kg) in locally consumed fruits from rainfed woody crops produced with organic fertilization and hand sorting. The highest CF (up to 2.2 kg CO_2 eq/kg of broccoli) were determined for vegetables produced using intensive agricultural practices that involved energy-intensive mechanization (Ingwersen, 2012); electricity consumption for irrigation and fertigation (Liu et al., 2010; Payen et al., 2015; Peano et al., 2015; Rana et al., 2019); consumption of fertilizers and agrochemicals (Iriarte et al., 2021); the use of auxiliary infrastructures, such as greenhouses and plastic covers (Payen et al., 2015; Rothwell et al., 2016); refined processing and packaging and long range refrigerated transport (Canals et al., 2008). Table 1 shows a strong variability in the contribution of the agricultural phase to the overall environmental performance of the vegetable products (between 7.4 % and 75 % of total CF). It should also be noted that some of the results reported in these studies

Table 1
Carbon footprint (CF) and life cycle stage contributions for fresh fruits and vegetables, as reported by different authors (homogenized to the FU of 1 kg).

Scope	Author	Product	Methods		CF	Farm	Factory	Transport	Consumption	EoL
					(kg CO_2eq/kg)	(%)	(%)	(%)	(%)	(%)
Cradle-to-market	Liu et al. (2010)	Pear	LCA	IPCC, NRE	0.06–0.30	55.4–93.9	3.0–43.9	0.7–7.6	–	–
	Ingwersen (2012)	Pineapple	LCA	IPCC, TRACI, USEtox, NRE	0.55	60.0	25.0	15.0	–	–
	Payen et al. (2015)	Tomato	LCA	ReCiPe	0.55	39.4	16.7	44.0	–	–
	Peano et al. (2015)	Strawberry	LCA	IPCC, NRE	0.55	58.7	33.3	3.6	–	–
		Raspberry			0.42	46.2	44.2	3.8	–	–
		Blueberry			0.44	38.2	52.7	3.6	–	–
	Rothwell et al. (2016)	Lettuce	LCA	CML	0.25–0.90	24.0–91.8	3.5–54.0	3.3–22.0	–	–
	Rana et al. (2019)	Sweet cherry	CF	IPCC	1.17	75.7	19.7	–	–	4.60
	Iriarte et al. (2021)	Apple	LCA	ILCD	0.54	11.8	16.5	71.7	–	–
Cradle-to-grave	Canals et al. (2008)	Broccoli	LCA	CML	2.22	7.4–26.8	1.7–5.2	12.7–15.3	50.4–60.7	9.3–11.4
		Lettuce			0.57–0.74	12.9–29.1	10.6–13.4	33.5–44.9	10.6–12.9	13.3–16.3
	Svanes and Johnsen (2019)	Apple	LCA	CML	0.46	41.0	20.3	19.6	15.4	3.8
		Sweet cherry			0.64	45.4	22.7	14.5	11.4	6.0
		Plum			0.88	57.6	17.5	12.7	8.2	4.0
	Parajuli et al. (2021)	Fresh potato	LCA	ReCiPe	0.77	15.7	12.7	25.7	45.9	− 0.5
		Fresh tomato			0.71	25.0	20.0	27.0	28.0	0.0

LCA: Life Cycle Assessment. CF: Carbon footprint. IPCC: Intergovernmental Panel on Climate Change. NRE: Non-Renewable Energy. TRACI: Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts. USEtox: UNEP/SETAC scientific consensus model for characterizing human toxicological and ecotoxicological impacts of chemical emissions in life cycle assessment. CML: Center of Environmental Science of Leiden University. ILCD: International Reference Life Cycle Data System.

could be questioned, since they do not apply the latest protocols for the analysis of biobased products (e.g., European Commission - Product Environmental Footprint (PEF)) (Zampori and Pant, 2019) and consider plant products as CO_2 sinks.

The post-harvest stage considers the processes that take place in the vegetable processing plant and include product reception, handling (sorting and/or sizing), packaging and cold storage prior to shipping to the retailer and final consumer. From the results shown in Table 1, the contribution of this processing plant to the overall CF of the vegetable product varies considerably (between 3.5 and 54 %), depending on the net emissions associated with other life cycle stages and the processing requirements of the product considered. Two factors contribute most to the CF of this factory phase: the production of the packaging material (Canals et al., 2008; Ingwersen, 2012; Payen et al., 2015; Peano et al., 2015; Rana et al., 2019; Rothwell et al., 2016; Svanes and Johnsen, 2019), and the electricity consumed in cooling operations (Liu et al., 2010; Parajuli et al., 2021; Rana et al., 2019; Iriarte et al., 2021).

The contribution of the transport phase also varies greatly, being mainly influenced by the distance and means of transport (highest emissions per km·t for refrigerated road transport and lowest for sea and rail) (Boschiero et al., 2019). For road transport, fuel type has also been reported to influence environmental performance, with heavy-duty vehicles powered by compressed natural gas (CNG) and electric/hybrid technologies exhibiting lower CF than diesel vehicles (Gustafsson et al., 2021; Ravigné and Da Costa, 2021; Rial and Javier, 2021; Wolfram and Wiedmann, 2017). Thus, the transportation stage in locally consumed pears (Liu et al., 2010) and lettuce (Rothwell et al., 2016) contributed to only 0.7 % and 3.5 % of the total carbon emissions of those products, respectively. In contrast, refrigerated international road transport of sweet cherries (Svanes and Johnsen, 2019) or lettuces (Rothwell et al., 2016) caused contributions of 14.5 % and 22.0 %, respectively. The contribution of transport in the refrigerated transoceanic shipping of apples (13,890 km) amounted to 71.7 % of their total CF (Iriarte et al., 2021).

Girotto et al. (2015) and Papargyropoulou et al. (2014) described the relationship between food waste and environmental footprint. The contribution of the End of Life (EoL) phase depends largely on the quantity and type of the by-products generated, and also the management scenarios considered. Thus, some authors have described small emission savings (− 0.5 %) due to the credits generated by the use of organic residues for animal feeding (Parajuli et al., 2021). Other authors described significant CF contributions (up to 16.3 %) as they considered emissions derived from human excretions and wastewater treatment requirements (Canals et al., 2008). Most of the food waste is landfilled, contributing not only to direct CF emissions but also to water pollution due to nitrogen (N) and phosphorus (P) leaching. Utilizing these residues for other commercial purposes reduces the impact of the food products throughout their value chain and may also provide a source of income that sustains the economic viability of the product. One option is to use food residues as animal feed (Ferguson, 2019). The FAO (2021) reported that 1.25 billion tons of food waste were used as animal feed. Other applications for food by-products include composting and energy valorization through anaerobic digestion for biogas production (Rojo et al., 2021) or direct combustion (Prasad et al., 2020). Cherubin et al. (2018) estimated that European food and crop residues could produce up to 12,528 MBTU (Mega British Unit) of energy.

In this context, the aim of the present study is to quantify the environmental impact of the post-harvest stage of two fresh vegetable products, representatives of the horticultural sector, that are widely produced and consumed in south-eastern Spain, and extensively exported throughout Europe. These results should identify those processes contributing the most to the environmental performance of these products and have the greatest potential for improvement. A more detailed description of these objectives is included in Section 2.1. Goal definition, as required by ISO 14040 (ISO, 2006a). This research aims to perform a holistic assessment of the fresh vegetable post-harvest production system to optimize its environmental performance.

2. Methodology

The environmental analysis has been carried out using a life cycle approach in accordance with ISO 14040-14044:2006 (ISO, 2006a, 2006b). This section provides information about the decisions considered in the four stages of this standardized protocol: Goal and scope definition; Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation.

2.1. Goal definition

This work is an academic study funded by RTI2018–099139-B-C21 that aims to assess the environmental sustainability of the post-harvest stage of two fresh vegetable products produced in southern Spain, and to determine the potential benefits associated with improved practices.

Secondary more specific goals derived from this main objective include: i) evaluating the contribution of key life cycle stages and processes throughout the value chain of the system; ii) identifying the environmental categories most severely affected; iii) evaluating the benefits of improved packaging practices, including increased utilization of recycled materials and reusable packaging elements; iv) evaluating the benefits of shorter transport ranges and environmentally friendlier vehicles and means of transportation; v) evaluating the benefits of incorporating renewable energy into the processing plant; and vi) evaluating the benefits of advanced waste management practices.

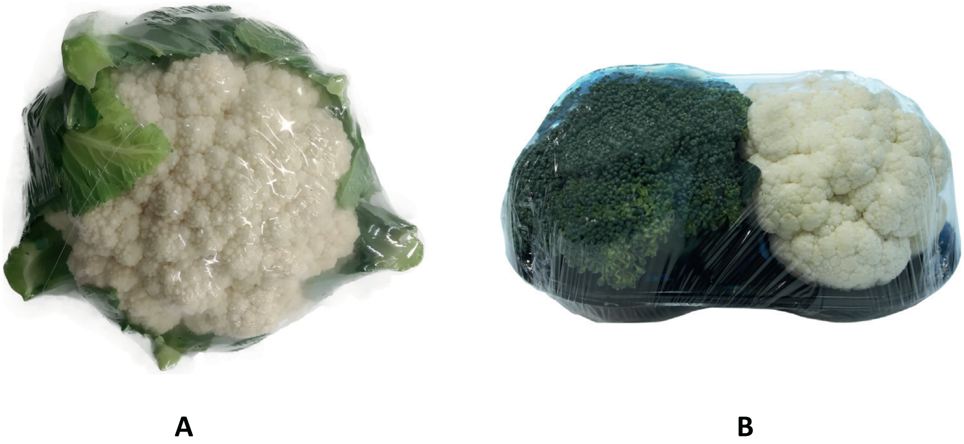


Fig. 1. Finished products evaluated in this study: A) Cauliflower (individually packed), and B) Brassica mix (one mini cauliflower and one broccoli packed together).

2.2. Scope definition

2.2.1. Methodological structure

The ISO 14040 and ISO 14044 protocols (ISO, 2006a, 2006b) have been implemented considering the methodological criteria for Product Environmental Footprint (PEF) recommended by the European Commission (EC) (Manfredi et al., 2012; Zampori and Pant, 2019).

2.2.2. System description and system boundaries

The analysis is based on two fresh vegetable products produced and commercialized by a company based in the Region of Murcia (southern Spain). These are: i) an individually packed cauliflower (*Brassica oleracea* var. *botrytis*) and, ii) a brassicas mix consisting of a small cauliflower and broccoli (*Brassica oleracea* var. *italica*) (approximately 50 wt% each) packed and commercialized together, as an example of another type of packaging. The analysis is based on data corresponding to the 2020 winter season (November to May), which led to the production of 2238 t of cauliflowers and 2256 t of brassicas mix. These values were described as representative of the fresh vegetable sector at present. Fig. 1 shows the visual appearance of these two finished products, ready for delivery to the customer.

Fig. 2 provides a life cycle representation of the system under study, describing the fact that it focuses on the activities that make up the post-harvest of the two fresh vegetable products considered, and leaving the agricultural stage, retailing and final consumption beyond the system boundaries. Table 2 illustrates the three stages considered in this post-harvest phase as follows: i) Upstream, considering the raw materials and the fabrication of the packaging components, including their transport and end-of-life management, ii) Core, including the activities carried out at the processing premises (reception, sorting and processing, packaging and cold storage), and iii) Downstream, involving the activities that occur beyond the gates of the processing factory, primarily the transport to the wholesale market.

Table 2
Life-cycle structure utilized in the environmental and energy analysis of the post-harvest stage of fresh vegetables.

Upstream packaging material	- Extraction of raw materials and manufacturing of packaging materials - Transport of packaging materials to factory (50 km). - End-of-life of packaging materials.
Core factory EoL	- Energy consumption at the processing factory (including reception, sorting, processing, packaging, and cold storage). - Vegetable waste management.
Downstream transport	- Refrigerated transport (national and international) of packaged products from factory to market (including construction of vehicles and infrastructures, fuel extraction and production, and direct emissions).

The analysis of the processing factory (Core stage) only considers the electricity consumed, leaving other elements (e.g., construction and maintenance of equipment and infrastructures) beyond the system boundaries. The activities carried out in the processing factory include:

- Loading of fresh vegetable products (cauliflower and brassicas mix) into polypropylene (PP) plastic crates, which are then stacked on wooden pallets.
- Transport from the fields to the factory by road (30 km) in small trucks.
- Reception and discharging of pallets using electric forklifts.
- Cold storage of loaded pallets at 2 °C for an average 36 h.
- Mechanical unloading of vegetables onto conveyor belts to processing lines where they are manually stripped of their outer leaves and sorted according to size and quality.
- The processing line for the brassicas mix involves placing the fresh vegetables (small cauliflower and broccoli) on a polyethylene terephthalate (PET) tray and then heat shrink wrapping in PET film. The processing line for individual cauliflower only involves the heat shrink wrapping.
- The wrapped products are packed into reinforced cardboard boxes (each one containing 10 units), which are then palletized and strapped with PP strips (each pallet contains 60 cardboard boxes).
- The palletized products are stored at 2 °C for an average of 48 h prior to shipping to their destination.

2.2.3. Description of base case and advanced scenarios

In order to structure this study, a base case scenario has been defined for the cauliflower and the brassicas mix which describes a conventional

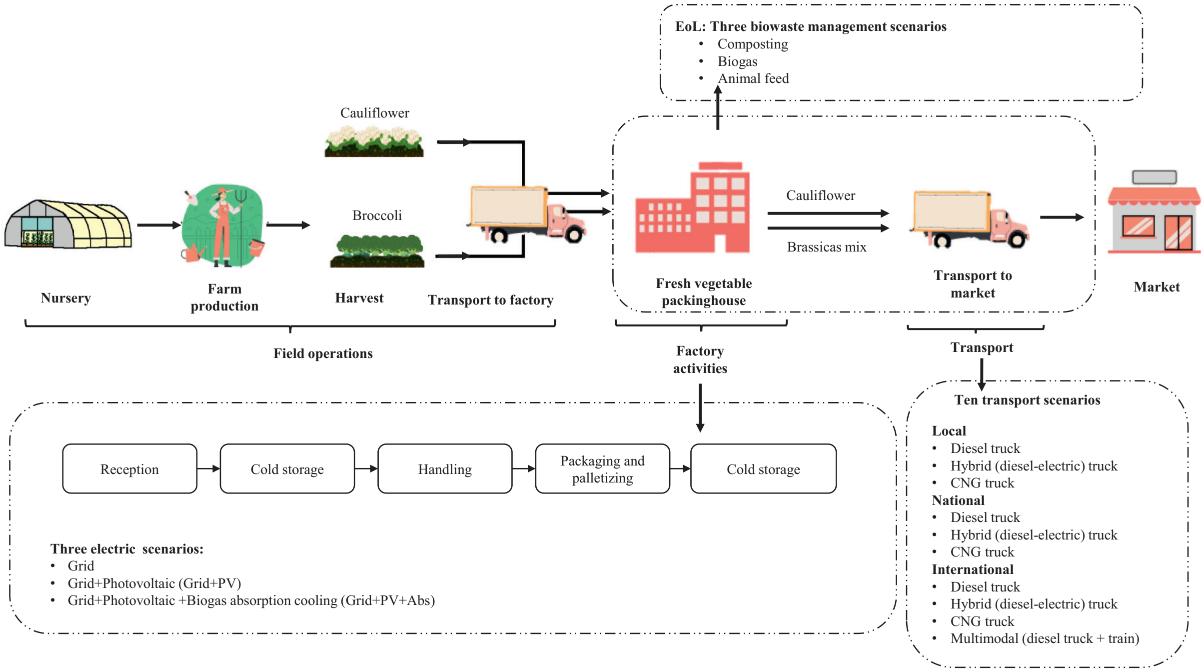


Fig. 2. Life-cycle diagram and system boundaries of the fresh vegetable systems considered in this study: cauliflower (individually packed) and brassicas mix (mini cauliflower and broccoli packaged together). CNG: compressed natural gas.

situation as it occurs at present. Advanced scenarios have been built, with each one considering the use of improved practices for the packaging of vegetable products, type of energy consumed at the processing factory, transport to wholesale market and management of organic residues. To avoid repetition, the present paper focuses only on the advanced scenarios applied to the cauliflower. A general description of these scenarios is provided below, and a quantitative analysis of the inventories involved is included in Section 2.3.

2.2.3.1. Energy scenarios at the processing factory. The base case scenario contemplates that the electricity consumed at the factory comes directly from the grid (Spanish electricity mix). The advanced scenarios consider the installation of roof-mounted photovoltaic (PV) panels to generate some of the power consumed at the factory and the incorporation of a biogas absorption plant to provide all the cooling demanded by the factory.

2.2.3.2. Packaging scenarios. The base case scenario involves the current situation where the cauliflower is individually packed in PET film, and then packed in cardboard boxes and onto pallets prior to shipping to the customer (the brassicas mix included an additional PET tray). Recycled contents and EoL management rates considered the existing situation in Spain. The improved packaging scenario involved the replacement of cardboard boxes with reusable plastic (PP) crates.

2.2.3.3. Vegetable waste management scenarios. During the sorting and processing of the fresh vegetables, 13 wt% of the cauliflower and 16 wt% of the brassica mix are discarded, representing a total of 651.8 t of organic waste throughout the winter season. The base case scenario for the management of this waste involves composting and the use of the resulting compost for soil conditioning. The improved scenarios consider the anaerobic digestion of the organic waste for biogas and electricity generation, and valorization for its nutritional value as animal feed.

2.2.3.4. Transport scenarios. The base case scenario for transport considers national delivery (500 km) using conventional EURO6 heavy load vehicles (16–32 t) running on diesel fuel. Alternative transport distances include local range (50 km) and international range (2470 km, equivalent to Cartagena to Berlin, Germany). Alternative transport technologies include similar heavy-load vehicles running on CNG and diesel-electric hybrid technology, and a multimodal option combining the use of road and rail transport.

2.2.4. Functional unit

The functional unit (FU) considered in this study is 1 kg of fresh vegetable product (either cauliflower or brassicas mix) delivered to the wholesale market in its commercial format, as suggested by the Product Category Rules for agriculture products (Environdec, 2020).

2.2.5. Multifunctionality and allocation

The allocation strategy followed in the construction of the LCA models followed the requirements of ISO 14040:2006 (ISO, 2006a) . Thus, to allocate the electricity consumed by each product in the processing plant, a direct allocation was made for those processes exclusive to the products considered (e.g., packaging of cauliflower or brassicas mix). For all other shared processes and consumptions (e.g., offices, lighting, cleaning, etc.), a mass allocation approach was used, considering that the cauliflower and the brassicas mix represented 12.0 wt% and 12.1 wt%, respectively, of the factory's entire output. A system expansion approach was used to calculate emission savings associated with the pouring of PV electricity surpluses into the grid and the management of organic residues generated at the processing factory.

2.2.6. Environmental impact assessment methodologies and impact categories

The EF 3.0 v.1 Life Cycle Impact Assessment (LCIA) methodology (Fazio et al., 2018) was used in this study, as recommended by the European Commission in its latest Product Environmental Footprint (PEF) Guide (Zampori and Pant, 2019). To facilitate the discussion of results, only four of the 16 midpoint impact categories considered in this method have been presented in this paper: climate change, photochemical ozone formation, acidification, and freshwater eutrophication. This selection was based on the recommendations of the Product Category Rules (PCR) for agricultural products published by Environdec (Environdec, 2020). However, to enable a broader view of the environmental performance of the systems, our analysis also considered the normalized values of chosen midpoint impact categories and aggregated single score indicator using normalization and weighting factors proposed by the same EF 3.0 methodology, and also the Cumulative Energy Demand (CED) indicator, which provides an energy perspective to the systems (Frischknecht et al., 2007).

2.2.7. Inventory data collection

As explained, the foreground inventory data was supplied by a company based in southeast Spain (Cartagena, Murcia) dedicated to the cultivation, processing, packaging, and commercialization of fresh vegetable products, and referred to the 2020 winter season (November to May). The inventory data for the processing factory only considered electricity consumption. These values were extracted from the energy audit carried out in compliance with the factory's energy management system (ISO-UNE ISO 50001, 2018). Organic waste generation was reported per product by the producers and the monthly figures reported for the factory. Packaging (type, mass, capacity, number of uses) and transportation (distances, means, type) inventory data were provided directly by the company.

Background inventory data for packaging materials, electricity use, stationary and mobile refrigeration, and transport were sourced from Ecoinvent 3.6 (Hischier et al., 2007). Individual datasets were selected and adapted to ensure geographical and technological representativeness, considering the electricity mix for Spain in 2020 (REE, 2021). The environmental footprint of heavy-duty vehicles running on CNG was modelled adapting the Ecoinvent v3.6 dataset for 16–32 t Euro6 diesel heavy-duty vehicles to the exhaust emissions reported in the Handbook Emission Factors for Road Transport (HBEFA) (Benedik et al., 2019). Heavy-duty commercial vehicles running on hybrid diesel-electric technology were modelled considering the use of Li-ion batteries, consumption values reported by Syed et al. (2019) and exhaust emissions reported by the European Environment Agency for diesel trucks (Leonidas and Zissis, 2019). A more detailed description of the modelling of these vehicles can be found in the Supplementary material.

2.2.8. Others

The LCA has been modelled using SimaPro v9.1.1. software (PRé Consultant, 2021).

2.3. Life cycle inventory analysis

2.3.1. Inventory data for packaging materials

Table 3 details the packaging materials considered in this study, as determined using a bottom-up approach:

i) Cauliflower: each unit is wrapped in 1.13 g of polyethylene terephthalate (PET) film. Ten units are packed into a cardboard box and 60 boxes are stacked on each wooden pallet.
ii) Brassicas mix: each pack (consisting of a small cauliflower and a small broccoli) is placed on a 10.4 g PET tray (100 % recycled) and wrapped in 2.07 g of PET plastic film. Ten packs are loaded into each cardboard box and 60 boxes are stacked onto each wooden pallet.

Two scenarios were considered for the packaging materials as follows:

i) Conventional packaging (base case) scenario considered a recycled content (%) in the packaging materials (Table 3) as stated by the company and the EoL options as published by the Spanish Ministry for the Environment (MITECO, 2019)

Table 3

Inventory analysis of packaging materials used in the fresh vegetables.

Materials	Recycled content (%)	EoL[a] (%)	Cauliflower (kg/FU)	Brassicas mix (kg/FU)
PET				
Film	0	R: 51.5/L:33.2/I: 15.3	5.21E-03	6.90E-03
Tray	100	R: 51.5/L:33.2/I: 15.3	–	3.45E-02
PP				
Strap	0	R: 51.5/L:33.2/I: 15.3	3.66E-04	5.56E-04
Cardboard				
Box	89	R: 72.9/L:23.6/I: 3.5	8.79E-02	6.67E-02
Reinforcements	89		6.44E-03	4.89E-03
Wooden Pallet	0	R:66.9/L:21.4/I:11.7	7.63E-03	5.79E-03

[a] End-of-life (EoL) management data (R = recycling, L = landfill and I = incineration with energy recovery) are derived from statistics published by the Spanish Ministry for the Environment (MITECO, 2019).

Table 5

Electricity inventory of the processing factory during the winter season, including total consumption, PV generation, PV onsite consumption, and PV surplus (poured into the grid).

	PV						
	Consumption	Generation		Used onsite		Surplus	
	kWh	kWh	%	kWh	%	kWh	%
2019 November	103,974	19,433	18.7	18,117	93.2	1316	6.8
2019 December	175,510	13,446	7.7	13,302	98.9	144	1.1
2020 January	174,021	20,308	11.7	19,123	94.2	1184	5.8
2020 February	156,824	22,699	14.5	21,233	93.5	1466	6.5
2020 March	150,361	26,787	17.8	24,316	90.8	2472	9.2
2020 April	145,029	26,609	18.3	24,076	90.5	2533	9.5
2020 May	111,340	33,546	30.1	26,897	80.2	6649	19.8
Total	1017,059	162,829		147,065		15,764	
Monthly average	145,294	23,261	17.0	21,009	91.6	2252	8.4

ii) Advanced packaging scenario describing the substitution of cardboard boxes with reusable plastic crates subjected to 150 utilization cycles prior to being discarded and managed as all other plastic materials (51.5 wt% recycling, 33.2 wt% landfill and 12.2 wt% incineration).

2.3.2. Inventory data for the processing factory

Table 4 provides a breakdown of the electricity allocated to each of the products and stages during the processing stage. The results show a similar consumption for the cauliflower and the brassicas mix (5.32E-02 kWh/kg), of which 42.0 % corresponded to cooling, 48.3 % to the different activities carried out in the processing lines (reception, sorting, processing, and packaging) and 9.7 % to other generic functions (lighting, office applications, cleaning, etc.).

The inventory data used in each of the three energy scenarios were as follows:

i) Grid (base case): considering the technology mix for Spain in 2020: nuclear (21.8 %), wind (21.5 %), natural gas combined cycle (19.7 %), cogeneration (10.6 %), reservoir hydraulic (12.0 %), pumped hydraulic (1.75 %), photovoltaic (5.98 %), concentrating solar power (1.78 %), coal (1.97 %), fuel and gas (2 %) and others (1.75 %) (REE, 2021).

ii) Grid + PV: involving the installation of a roof-mounted photovoltaic (PV) system to provide some of the electricity consumed by the factory. This scenario was modelled using System Advisor Model (SAM) SSC v252 software from the U.S National Renewable Laboratory (NREL, 2021) considering as a limiting factor the size of the factory roof (1637 m^2). The system considered two arrays of 350 PV modules (280 W) each, for a total peak power of 196 kW, yielding a total of 162,829 kWh during the winter season. Table 5 provides a monthly breakdown of the power consumed, generated by the PV system and poured into the grid. The results showed a total power consumption during the winter season of 1017 MWh, a PV contribution of 14.5 % and PV surpluses of 15,764 kWh, which were assumed to have been poured into the grid (San Miguel and Corona, 2018; Zakeri et al., 2021), amounting to 8.4 % of the total generated. A full description of the PV and energy model leading to these results has been included in the Supplementary material.

Table 4

Electricity inventory allocation for fresh cauliflower and brassicas mix at the processing factory.

Activities	Cauliflower		Brassicas mix	
	kWh	kWh/kg	kWh	kWh/kg
Cold storage	49,964	2.23E-02	50,414	2.23E-02
Processing	57,405	2.57E-02	57,921	2.57E-02
Other functions	11,594	5.18E-03	11,698	5.18E-03
Total	118,963	5.32E-02	120,033	5.32E-02

iii) Grid + PV + Abs: considering a higher integration of renewable energy in the processing factory which included the PV system described above plus an absorption system designed to meet all the refrigeration needs (including raw vegetables and finished products). This involves the installation of three 100 kW absorption cooling systems, with a performance coefficient $\eta = 0.6$, running on biogas produced from the organic by-products generated onsite. Electricity savings from the incorporation of the absorption system represent 42.0 % of the original demand.

2.3.3. Inventory data for vegetable waste management (EoL)

The inventory data for the three EoL scenarios considered in this study are as follows:

i) Composting scenario (base case) assumes the aerobic digestion of the biowaste at a nearby facility and using the resulting compost as a replacement for ammonium nitrate (fertilizer). A mass substitution factor of 1/0.015 was used which considered the nitrogen content of these two products (AGROPAL, 2021).

ii) Biogas scenario involves the mesophilic anaerobic digestion of the organic residues in a nearby plant in order to produce biogas, which is subsequently used to produce electricity. The analysis considers a Lower Heating Value (LHV) for the biogas of 13.5 MJ/kg and assuming a methane (CH_4) generation potential for cauliflower and broccoli of 0.022 m^3 CH_4/kg and 0.029 m^3 CH_4/kg, respectively (Jørgensen, 2009; Oosterkamp, 2020).

iii) Animal feed scenario considers the vegetable residues as a substitute for maize in animal feed. Replacement factors have been calculated on the bases of the nutritional values (kcal/kg) provided by the United States Department of Agriculture (USDA) as follows: 260 kcal/kg of cauliflower, 269 kcal/kg of broccoli) and 860 kcal/kg of maize (USDA, 2021).

2.3.4. Inventory data for transport

The inventory data for transport scenarios considered in this study are as follows:

i) National range distribution is the most common for this company and considers a 500 km distance covered by road using heavy-load (16–32 t) vehicles running on diesel (base case) and advanced transport technologies (CNG and hybrid diesel-electric technology with similar heavy-load vehicles).

ii) Local range distribution considers a 50 km distance covered by road using heavy-load (16–32 t) vehicles running on diesel and including the advanced transport technologies.

iii) International range distribution considers a 2500 km distance. This distance can be covered: i) by road with heavy-load (16–32 t) vehicles running on diesel and advanced technologies; or by, ii) multi-modal,

Table 6
Characterized environmental and energy impact assessment per FU (1 kg) corresponding to the post-harvest of fresh cauliflower and brassicas mix for base case scenario[a].

Product	Impact category	Unit	Total	Packaging materials	Factory	Composting	National transport
Cauliflower	Climate change	kg CO_2eq	2.38E-01	1.43E-01	1.02E-02	−8.54E-03	9.40E-02
	Photochemical ozone formation	kg NMVOC eq	6.28E-04	3.43E-04	3.03E-05	−2.31E-05	2.78E-04
	Acidification	mol H+ eq	1.02E-03	4.72E-04	5.60E-05	1.89E-04	3.06E-04
	Eutrophication, freshwater	kg P eq	4.74E-05	3.77E-05	3.79E-06	−1.06E-06	6.94E-06
	CED	MJ	4.21E+00	2.24E+00	4.96E-01	−4.51E-02	1.52E+00
Brassicas mix	Climate change	kg CO_2eq	2.94E-01	1.99E-01	1.02E-02	−1.07E-02	9.60E-02
	Photochemical ozone formation	kg NMVOC eq	7.12E-04	4.27E-04	3.03E-05	−2.91E-05	2.84E-04
	Acidification	mol H+ eq	1.21E-03	6.00E-04	5.60E-05	2.38E-04	3.12E-04
	Eutrophication, freshwater	kg P eq	6.08E-05	5.12E-05	3.79E-06	−1.33E-06	7.09E-06
	CED	MJ	4.84E+00	2.84E+00	4.96E-01	−5.67E-02	1.55E+00

[a] Base case scenario: handling/processing of vegetables using grid electricity, packaging materials (production and EoL management), composting of vegetable residues and national transport (500 km) by road using diesel-powered vehicles.

considering that 70 % of this distance is covered by rail and 30 % by road with heavy-load vehicles powered by diesel.

The transport volume generated by each product considers not only the vegetable mass but also its packaging, representing 7.9 wt% of the cauliflower and 10.6 wt% of the brassicas mix.

2.3.5. Uncertainty analysis

In addition to the environmental sustainability analysis, an uncertainty analysis was performed on the cauliflower production base case scenario to determine the variation in the background data in terms of coefficient of variance (CV) expressed as a percentage. The Monte Carlo simulation is a widely used to evaluate the uncertainty in LCA studies (Ponsioen et al., 2020). This simulation was used to calculate the uncertainty of the data at a 95 % confidence interval using SimaPro v9.1.1. software (PRé Consultant, 2021).

3. Results and discussion

3.1. Environmental assessment of the base case scenario

This first part of this section is dedicated to analyzing the environmental footprint of the base case scenario defining the post-harvest stage of two vegetable products: cauliflower and brassicas mix. This involves the handling and processing of the vegetables using electricity from the grid, EoL management of packaging materials according to standard practices, national range transport (500 km) by road using conventional diesel-powered vehicles, and composting of vegetable residues.

3.1.1. Characterized impacts

Table 6 shows the environmental footprint generated by the post-harvest system and Fig. 3 illustrates the contribution of the life cycle stages for this base case scenario. The characterized impacts generated by the cauliflower were as follows: climate change 2.38E-01 kg CO_2 eq/kg, photochemical ozone formation 6.28E-04 kg MNVOC eq/kg, acidification 1.02E-03 mol H+ eq/kg, and freshwater eutrophication 4.74E-05 kg P eq/kg, and CED 4.21 MJ/kg.

The results show that most of this CF is associated with the packaging material (57.8 %) and the national transport (38.0 %). The electricity consumed at the processing factory contributed to only 4.1 % of the total CF while the recovery of biowaste involved carbon savings of −3.5 % due to its composting and use for soil conditioning. The packaging material dominated all impact categories (up to 77.9 % of eutrophication) while the contribution of the transport stage typically ranged between 30 and 40 % of the total. The negative effect of the EoL stage on the acidification category, which is associated primarily to the emission of ammonia during the composting process, should also be noted.

The CF of the brassicas mix was 19.0 % greater than that observed for cauliflower and the impact of national transport was also slightly higher due to its additional packaging (PET tray). The composting provided a higher saving in the brassica mix since the discard was higher (16 wt%) than in cauliflower (13 wt%). To understand the magnitude of these impact values, the CF of the pre-harvest stage of cauliflower and broccoli produced in France were estimated to be 2.96 E-01 kg CO_2 eq/kg and 4.18E-01 kg CO_2 eq/kg, respectively (from Agribalyse 3). Based on these results, it may be approximated that the post-harvest stage represents around 44.6 % of the CF generated by the entire life cycle of the cauliflower and 41.3 % for the brassicas mix.

3.1.2. Normalized and aggregated post-harvest impacts assessment

Fig. 4 shows the normalized impact values for the base case scenario of the cauliflower. The results show a significant contribution from all categories, with higher relative values for freshwater eutrophication and climate change. These results evidence the strong contribution primarily from the packaging material and to a lesser degree from the transport phase. The brassicas mix followed a very similar pattern (data not shown).

Fig. 5 confirms the dominance of the packaging material and the transport in the environmental profile of the post-harvest phase of fresh vegetable products when all of the 16 impact categories included in the EF3.0 LCIA methodology were considered in the single score indicator. The prevalence of the packaging material was more notable in the brassicas mix as it incorporated an additional PET tray. The contribution of the processing factory activities and the management of organic residues to the environmental performance of the post-harvest stage of fresh vegetables was very limited. Of all the impact categories considered by the single score indicator, the results showed strong contributions from climate change, freshwater ecotoxicity, and the use of fossil and mineral resources. The results indicate that it would be necessary to explore these categories in greater detail.

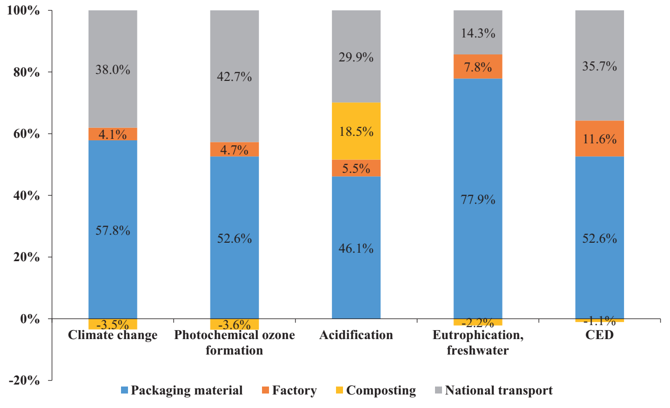


Fig. 3. Contribution of different stages to the post-harvest of fresh cauliflower (base case scenario).

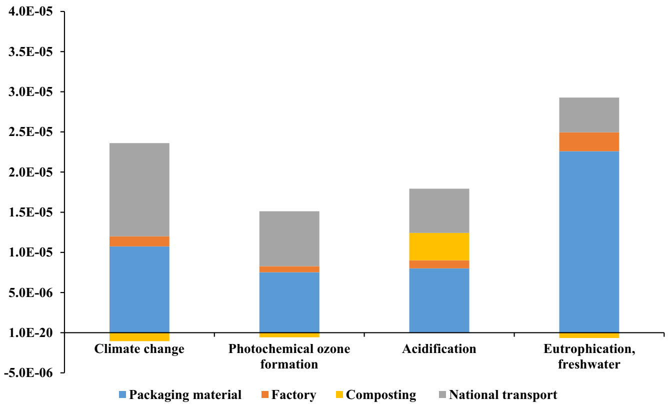


Fig. 4. Normalized impacts per FU (1 kg) of cauliflower in the post-harvest stage (base case scenario).

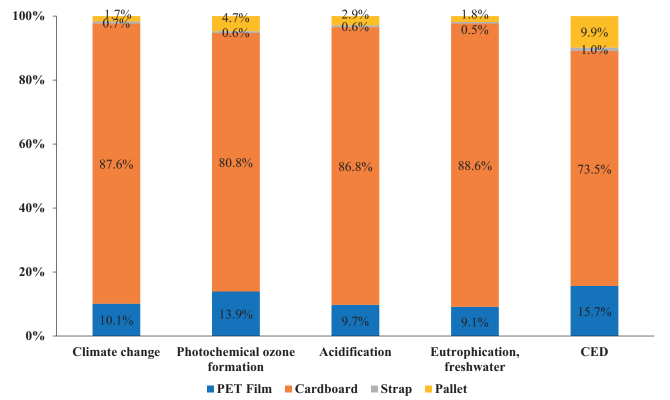


Fig. 6. Contribution of components employed in the packaging of fresh cauliflower per FU (1 kg) (base case scenario).

3.2. Environmental assessment and advanced scenarios of packaging

Fig. 6 provides a more in-depth analysis of the environmental performance of the packaging materials used for the cauliflower. The results show that cardboard was the main contributor to all impact categories (between 73.5 and 88.6 %), which was far more than the next, the PET film (between 9.1 and 15.7 %), whilst the contribution of all other elements (pallet and film strap) was more marginal.

The CF of the packaging employed in the brassica mix was 35.2 % higher than that determined for the cauliflower (1.99E-01 kg CO_2 eq/kg compared to 1.43E-01 kg CO_2 eq/kg), due to the inclusion of the PET tray. The contribution of this element in the environmental consideration amounted to between 20.4 % and 26.4 %.

Table 7 shows that the substitution of single-use cardboard boxes with reusable plastic crates significantly reduced the CF of the cauliflower packaging stage from 1.43E-01 kg CO_2 eq/kg to 2.53E-02 kg CO_2 eq/kg. As a result, the CF of the packaging stage decreased by 82.3 %, and reductions of between 65.3 and 83.5 % were observed for the other impact categories.

Fig. 7 illustrates the overall improvement in the environmental performance of the packaging stage as a result of substituting the single-use carboard box with the reusable plastic crate. The single score indicator decreased by 84.5 % using reusable plastic crates rather than single-use cardboard boxes due to a lower impact primarily in the climate change, freshwater eutrophication and resources use (both minerals and metals, and fossil fuels). Similar impact savings were reported by Rothwell et al. (2016) who noted that the carboard components of the packaging were responsible for 41.4 % of the total CF generated by lettuces, achieving reductions of up to 97.0 % when the single-use cardboard was replaced by reusable plastic crates. López-Gálvez et al. (2021) also described the environmental benefits of using reusable plastic crates in the transportation of fresh fruits and vegetables, obtaining a reduction of 89.8 % in the CF.

Based on these results it can be suggested, firstly, to replace the single-use carboard box for the reusable plastic crate, because it provides greater reductions in all the impact categories assessed and throughout the packaging life cycle (production and its end of life). Secondly, an evaluation is needed to determine whether all the packaging included is necessary to maintain optimum vegetable quality. Therefore, over packaging the product should be avoided, thus reducing the impact.

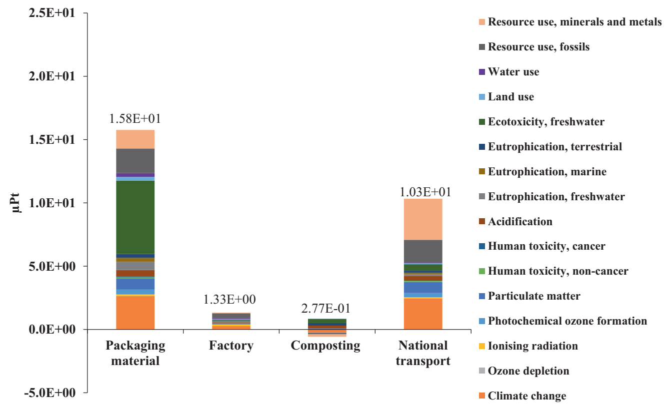


Fig. 5. Single score indicator describing the environmental performance per FU (1 kg) for different stages of the post-harvest of cauliflower (base case scenario).

3.3. Environmental assessment and advanced scenarios of processing factory

As mentioned before, the processing factory stage refers to the energy consumed at the company premises where the fresh vegetables were received, sorted, packaged, palletized, and cold stored prior to shipping to the wholesale market. Table 8 shows the environmental impacts generated by this energy in the base case scenario where the electricity comes directly from the grid (Spanish electricity mix) and the two scenarios describing partial electricity generation from rooftop PV (Grid + PV) and cold production using absorption technology (Grid + PV + Abs).

The integration of PV panels reduced the CF of the processing factory stage by 11.9 %, while savings in other relevant impact categories amounted to between 6.0 % to 9.8 %. Rothwell et al. (2016) and Boschiero et al. (2019) reported carbon savings of around 50 % when they replaced the electricity consumed in a vegetable processing plant with 100 % renewable energy, while Colley et al. (2020) reduced the CF by 34 % when replacing 14 % of the grid with renewables.

The integration of absorption cooling technology (Grid + PV + Abs) further improved the environmental performance of the processing factory stage. The CF was reduced by 67.2 % and the impact in other relevant

Table 7
Environmental and energy assessment of the improved packaging scenarios per FU (1 kg) of cauliflower: comparing impact values and savings in the packaging stage associated with the replacement of a single-use cardboard box with a reusable plastic crate.

Impact category	Packaging with cardboard		Packaging with reusable plastic crate	
	Units	Impact	Impact	% savings
Climate change	kg CO_2eq	1.43E-01	2.53E-02	−82.3
Photochemical ozone formation	kg NMVOC eq	3.43E-04	8.29E-05	−75.8
Acidification	mol H+ eq	4.72E-04	8.65E-05	−81.7
Eutrophication, freshwater	kg P eq	3.77E-05	6.21E-06	−83.5
CED	MJ	2.24E+00	7.76E-01	−65.3

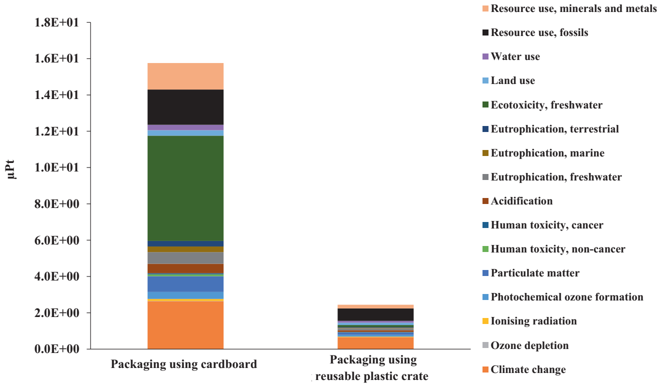


Fig. 7. Environmental single score indicator of packaging scenarios per FU (1 kg) of cauliflower: comparing single use cardboard vs. reusable plastic crate.

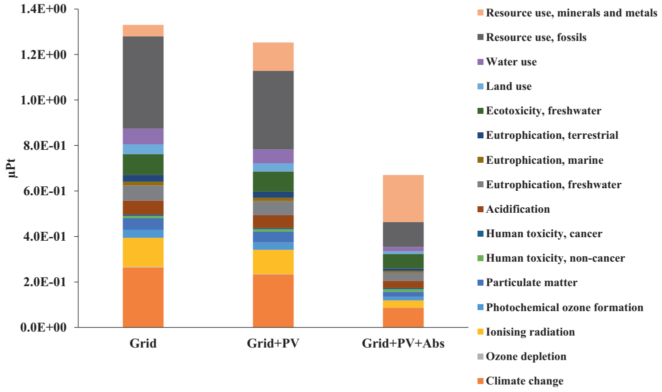


Fig. 8. Environmental single score for three alternative energy electricity scenarios for electricity consumed in the factory per FU (1 kg) of cauliflower. Grid: Spanish electric mix. PV: Photovoltaic panels. Abs: Absorption system.

categories fell by between 48.4 % and 72.1 %, with the highest reduction being attributed to the CED indicator. Other authors also concur that the lower energy demand of absorption cooling technology enables reductions in climate change and CED impact categories (Hwang, 2004; Li et al., 2019; Anand et al., 2014).

Fig. 8 illustrates the overall improvement of the environmental performance of the processing factory stage as a result of replacing grid electricity with renewable energy resources. The single score indicator of the Grid + PV scenario was reduced by 5.8 % due primarily to savings in the use of fossil-fuel resources and climate change. The Grid + PV + Abs scenario achieved higher single score reductions (49.6 %) due to further savings in nearly all impact categories. However, it should be noted that the integration of renewables resulted in higher impact values in the use of minerals and metals category, which is related to the consumption of critical metals, primarily copper. Despite the overall benefits, a slight increase in other impact categories such as non-cancer human toxicity and freshwater eutrophication was also associated with the use of renewable energy. As a result of this analysis, it can be deduced that the electricity grid consumption in the factory should be reduced, thus minimizing the cost of electricity consumption, and an investment should be made to integrate renewable energies. This industry requires a high demand of electricity to produce the cold for fresh vegetables and using absorption cooling equipment, significant reductions in the environmental impact can be obtained with minimal consumption from the grid.

3.4. Environmental assessment and advanced scenarios of organic waste management

Table 9 describes the environmental performance of alternative management scenarios for the organic waste generated at the vegetable processing factory. The results for cauliflower show negative impacts (emission savings) for the base case scenario, which involved aerobic digestion of the residues and using the resulting compost to replace synthetic fertilizers. The exception to this rule was the acidification category, due to the emission of ammonia during the anaerobic digestion process, and nitrogen and sulphur oxide emissions generated by diesel combustion in the composting facilities.

The processing of the organic waste to generate biogas, used as a replacement for CNG, increased CF savings by 9.9 %. This scenario also improved the environmental performance of the waste management stage in other relevant impact categories (98 % in CED and 70.9 % in photochemical ozone formation). The positive impact of the composting process in the acidification category became negative (emission savings) when considering the anaerobic digestion of the waste. However, the biogas scenario generated higher emissions in the freshwater eutrophication category.

The animal feed scenario exhibited the best environmental performance, with the highest savings in all categories. Compared to the base case scenario (composting), utilizing the organic residues from vegetable processing for animal feeding reduced the CF by 69.0 % and other impact categories by 24.7 % for CED, and 89.1 % for freshwater eutrophication. Emission savings (−3.73E-04 mol H+ eq/kg) were also observed in the acidification category.

Fig. 9 illustrates the environmental performance of the alternative organic waste management scenarios using the aggregated single score. The results showed a positive impact in the composting scenario (base case) due to the prevalence of the impacts in categories such as freshwater ecotoxicity, terrestrial eutrophication, and acidification associated with the construction of the facilities and emissions derived from the operation of the aerobic digestion system. These positive impacts were not compensated by emission savings in other categories such as climate change and the use of resources (mineral, fossil, and water) derived from the replacement of synthetic fertilizers.

In contrast, the single score of the biogas scenario describes the overall environmental savings of this alternative, which were primarily associated with the use of fossil resources derived from the replacement of CNG by the biogas. The animal feed scenario achieved the best results due to the environmental savings associated with the replacement of corn. Only environmental benefits were obtained, and the savings were distributed throughout a wide range of impact categories, such as climate change, water use, resource use – minerals and metals and freshwater ecotoxicity.

Table 8
Environmental and energy assessment of improved electricity scenarios per FU (1 kg) of cauliflower: comparing impacts and savings to the processing factory stage associated with the replacement of the Grid (Spanish electric mix) with PV (photovoltaic panels) or Abs (absorption system).

Impact category	Units	Grid	Grid + PV		Grid + PV + Abs	
		Impact	Impact	% savings	Impact	% savings
Climate change	kg CO_2eq	1.02E-02	8.95E-03	−11.9 %	3.33E-03	−67.2 %
Photochemical ozone formation	kg NMVOC eq	3.03E-05	2.74E-05	−9.8 %	1.31E-05	−56.9 %
Acidification	mol H+ eq	5.60E-05	5.07E-05	−9.4 %	2.89E-05	−48.4 %
Eutrophication, freshwater	kg P eq	3.79E-06	3.56E-06	−6.0 %	2.07E-06	−45.4 %
CED	MJ	4.96E-01	4.51E-01	−8.9 %	1.38E-01	−72.1 %

Table 9

Environmental and energy assessment of improved EoL scenarios per FU (1 kg) of cauliflower: comparing impacts and saving in the EoL stage associated with the substitution of biowaste composting (environmental impact of composting and chemical fertilizer savings) with biogas (environmental impact of anaerobic digestion for biogas production and savings of CNG) and animal feed (corn savings).

Impact category	Units	Composting	Biogas		Animal feed	
		Impact	Impact	%savings	Impact	%savings
Climate change	kg CO_2eq	−8.54E-03	−1.13E-02	−9.9	−2.75E-02	−69.0
Photochemical ozone formation	kg NMVOC eq	−2.31E-05	−1.07E-04	−70.9	−1.18E-04	−80.5
Acidification	mol H+ eq	1.89E-04	−1.91E-04	−102.0	−3.73E-04	−150.8
Eutrophication, freshwater	kg P eq	−1.06E-06	6.44E-07	+17.5	−9.70E-06	−89.1
CED	MJ	−4.51E-02	−3.73E+00	−98.8	−9.67E-01	−24.7

Several researchers have reported on the environmental performance of alternative food waste management options. For instance, Keng et al. (2020) assessed the LCA of food waste composting, obtaining a CF of −5.3E-01 kg CO_2eq/kg due to the substitution of synthetic fertilizers with compost. Marcello et al. (2021) reported a mean value of −3.7E-01 kg CO_2eq/kg of food waste composting for chemical fertilizers and peat substitution. Li et al. (2018) evaluated the LCA of solid organic waste (manure, tomato residues, and corn stove) by anaerobic digestion, composting, or anaerobic digestion followed by composting, obtaining a range of −1.8E-01 to −2.9E+00 kg CO_2eq/kg of solid organic waste. That work included the savings of landfill and incineration treatments, heat, electricity, and chemical fertilizers. For anaerobic digestion, Eriksson et al. (2015) reported a CF of −6.1E-01 to −1.0E-02 kg CO_2eq/kg of food waste, by attributing the savings of diesel production and nitrogen fertilizers. Demichelis et al. (2019) obtained that by anaerobic digestion of 1 kg of fruit and vegetables −2.34E+00 kg CO_2eq were avoided, including the savings in electricity production. Concerning the animal feed waste scenario, Parajuli et al. (2021) and Eriksson et al. (2015) calculated the CF savings avoiding the production of corn, reducing the CF by 80 % and 88 % in comparison with fruit and vegetable compost. Salemdeeb et al. (2017) and Kim and Kim (2010) found that the use of food waste for wet animal feed reduced the CF by 99 % in comparison with food composting.

The best waste management option was animal feed, since greater environmental savings were obtained. In any case, the valorization of food waste for animal feed, biogas production or composting enhances the circularity of waste, increasing business opportunities. Therefore, this environmental assessment should be studied with the participation of all stakeholders to obtain more accurate data regarding the environmental benefits of food waste revalorization.

3.5. Environmental assessment and advanced transport scenarios

Table 10 describes the environmental behavior of conventional trucks (powered by diesel) and advanced transport technologies (CNG and hybrid diesel-electric powered vehicles) for the national range (500 km). The CF for the base case scenario (conventional diesel vehicles) was estimated to be 9.40E-02 kg CO_2eq/kg of cauliflower. This fell by 49.4 % when using hybrid (diesel-electric) trucks and by 65.7 % when using CNG-powered vehicles. The use of hybrid trucks reduced the damage in most categories and the CED of the transportation stage by 40.5 %, although the impact on freshwater eutrophication increased by 72.0 % due to the fossil-fuel sources of the grid electricity. The use of CNG trucks reduced the damage to all other categories significantly and decreased the CED of the transportation stage by 63.8 % in the CNG-powered vehicles. The best environmental performance in all the impact categories was for the CNG-powered vehicle, with emissions savings of up to 87.0 % in photochemical ozone formation.

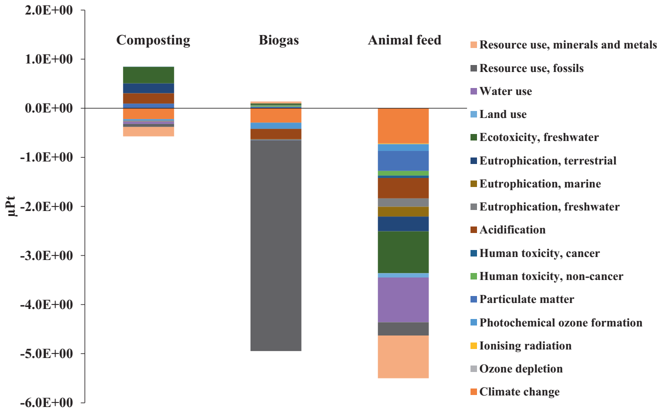


Fig. 9. Environmental single score for three EoL scenarios (composting, biogas, and animal feed) per FU (1 kg) of cauliflower.

Table 11 compares the base case scenario (500 km using conventional trucks powered by diesel) against local transport (50 km) using conventional trucks (diesel) and advanced technologies (CNG and hybrid diesel-electric powered vehicles). For the same transport technology (diesel), the results showed impact savings for local range delivery that were directly related with the distances involved (500 km for national and 50 km for local). Hence, 90 % savings were calculated for each of the impact categories. The use of hybrid and CNG-powered vehicles for local transport further increased the emissions savings, typically by 90–95 % compared to the national transport base case scenario. The environmental behavior of CNG vehicles was slightly better than hybrid (electric-diesel) vehicles, although the differences were not particularly significant.

Table 12 compares the national base case scenario (500 km using conventional trucks powered by diesel) with the international scenarios (2500 km) considering: i) road transport with conventional trucks (diesel) and with advanced technologies (CNG and hybrid diesel-electric powered vehicles), and ii) multimodal (70 % rail and 30 % by road with diesel trucks). The results show increments in CF of between 54.5 and 79.8 %. The lowest increase was for the CNG trucks, followed by the multimodal scenario and the highest increase corresponded to conventional diesel-powered vehicles.

As reported in other works, the CF of transport is linked with distance and type of transport. For instance, for local road distribution by truck, Rothwell et al. (2016) reported a CF of 8.25E-03 kg CO_2eq/kg of lettuce (39 km), while Liu et al. (2010) reported a CF of 4.20E-04 kg CO_2eq/kg of pear (80 km). Ingwersen (2012) reported 8.25E-02 kg CO_2eq/kg of pineapple for transportation of 500 km, while Svanes and Johnsen (2019) obtained a 9.02E-02 kg CO_2eq/kg of apple for transportation of 549 km. For greater distances, Parajuli et al. (2021) obtained a CF of 1.98E-01 kg CO_2eq/kg of potato for distribution of 1200 km by truck, and Canals et al. (2008) reported 2.82E-01 kg CO_2eq/kg of broccoli for distribution of 2600 km by truck. According to the means of transport, the work of Boschiero et al. (2019) obtained a CF of 7.60E-02 kg CO_2eq/kg of apple for a multimodal transport scenario (100 km by truck plus 1750 km by train) reducing the CF by nearly 73.0 % in comparison with international transport using conventional diesel trucks. All these values include the packaging weight, as in the present paper.

The environmental impact of heavy-duty trucks with different fuel options has been studied by several authors. Rial and Javier (2021) and Wolfram and Wiedmann (2017) performed a comparative LCA between diesel and hybrid vehicles obtaining carbon footprint reductions of 6.6 %

Table 10

Environmental and energy assessment of the improved national transportation scenarios per FU (1 kg) of cauliflower. Comparing impacts and savings associated with the replacement of diesel trucks with hybrid trucks (diesel-electric) or compressed natural gas (CNG) trucks.

Impact category	Units	Diesel	Hybrid		CNG	
		Impact	Impact	%savings	Impact	%savings
Climate change	kg CO_2eq	9.40E-02	4.76E-02	−49.4	4.36E-02	−65.7
Photochemical ozone formation	kg NMVOC eq	2.78E-04	2.33E-04	−16.0	1.73E-04	−87.0
Acidification	mol H+ eq	3.06E-04	2.91E-04	−4.7	1.65E-04	−83.4
Eutrophication, freshwater	kg P eq	6.94E-06	2.48E-05	+72.0	8.05E-06	−74.8
CED	MJ	1.52E+00	9.04E-01	−40.5	1.37E+00	−63.8

and 20.6 % respectively, compared to the diesel vehicle. Both studies concluded that the operation phase was the step that contributed most to the CF. In the case of electric or hybrid electric vehicles, the reductions in the CF depended on the carbon factor (CO_2eq/kWh) which is governed by the electricity grid in each country (Gustafsson et al., 2021). Ashnani et al. (2015), Ravigné and Da Costa (2021) and Gustafsson et al. (2021) performed a comparative LCA of diesel trucks versus CNG-powered vehicles, obtaining similar conclusions: CNG combustion and CNG extraction were the steps that contributed most to the total CF. However, the reductions in CF were 7.2 %, 5.0 % and 24.9 %, respectively. This variability in CF reduction is related to the energy sources used in its extraction and the production of CNG.

Fig. 10 presents the environmental performance of the alternative transport scenarios using the aggregated single score indicator. The single score for the national distribution (500 km) of cauliflower using diesel trucks was 1.03E+01 μP/kg. The results show how the overall environmental impact decreased by 7.6 % when using hybrid vehicles and by 13.2 % when using CNG-powered trucks.

This single score indicator decreased dramatically in the local distribution scenarios (by between 90.0 % and 92.3 %) and increased significantly in the international transport (by between 68.5 % and 79.8 %). In all distance ranges, the best environmental performance was always for CNG trucks, followed by hybrid and diesel-powered vehicles. The most environmentally conscious option for international transport was related to the use of multimodal transport, which involved 70 % of the 2500 km by rail and 30 % by road.

In all the cases, the most affected impact categories were climate change, use of fossil fuel resources and particulate matter (associated with fuel production and combustion), and use of mineral and metal resources (associated with truck production and maintenance).

As a conclusion to this analysis, the truck fleet should shift towards the use of fuels with a lower CF in their extraction and use, such as CNG. On the other hand, the reduction of kilometers traveled would be an option to decrease the impact, but this is difficult in a globalized society that demands a continuous food supply anywhere. Therefore, an optimized distribution network by rail would help to reduce the impact of international distribution.

3.6. Uncertainty analysis

An uncertainty analysis was carried out to evaluate the CV of the background inventory data on specific midpoint indicators, as used to model the cauliflower post-harvest scenario. The results showed a CV average of 14.3 %, obtaining 5.5 % for CED, followed by climate change (6.6 %), acidification (7.2 %), photochemical ozone formation (10.2 %) and freshwater eutrophication (42.1 %).

4. Conclusions

This study was focused only on the evaluation of the environmental impact of the post-harvest stage for fresh vegetables (handling, processing, packaging, storage, cooling, and transport to the final consumer, including the management of organic residues and packaging components at the end of their useful life). For the base case scenario for the fresh cauliflower and brassicas mix: grid electricity in the processing plant, composting of organic residues, national range transport and conventional packaging, the main conclusions are:

a) The CF of the post-harvest activities generated by the fresh cauliflower and brassicas mix amounted to 2.38E-01 and 2.94E-01 kg CO_2eq/kg, respectively. This represented 40–50 % of the CF associated with the entire value chain of the product, including the agricultural phase. Characterized emissions for other key impact categories (photochemical ozone formation, acidification, and freshwater eutrophication) and energy indicator (CED) are reported in this publication.
b) The life cycle stages contributing the most to the environmental performance of the post-harvest activities of these fresh vegetable products were the packaging material (57.8 % of CF) and the transport from the factory to the wholesale market (38.0 % of CF). Electricity consumption at the processing factory had a very limited contribution (4.1 % of CF) whilst the management of the organic residues involved small savings (−3.5 % of CF) due to the use of the resulting compost as a replacement for synthetic fertilizers. The significance of the packaging and transport stages was also observed in the analysis of other impact categories.
c) The cardboard employed as a packaging material for fresh vegetable products was responsible for most of the CF of this stage (up to 87.6 %) and was also responsible for most of the impact generated on other environmental categories.
d) Regarding the transport stage in national range distances, the results showed significant CF savings when using hybrid (electric/diesel) and CNG-powered vehicles (up to 65.7 %) compared to conventional diesel trucks.

Table 11

Environmental and energy assessment of the improved national transportation scenarios per FU (1 kg) of cauliflower. Comparing impacts and savings associated with the replacement of national distribution (500 km) with diesel trucks with local distribution (50 km) and different fuel options: diesel, hybrid or compressed natural gas (CNG).

Impact category	Units	National	Local					
		Diesel	Diesel		Hybrid		CNG	
		Impact	Impact	%savings	Impact	%savings	Impact	%savings
Climate change	kg CO_2eq	9.40E-02	9.40E-03	−90.0	4.76E-03	−94.9	4.36E-03	−95.4
Photochemical ozone formation	kg NMVOC eq	2.78E-04	2.78E-05	−90.0	2.33E-05	−91.5	1.73E-05	−93.8
Acidification	mol H+ eq	3.06E-04	3.06E-05	−90.0	2.91E-05	−90.5	1.65E-05	−94.6
Eutrophication, freshwater	kg P eq	6.94E-06	6.94E-07	−90.0	2.48E-06	−64.3	8.05E-07	−88.4
CED	MJ	1.52E+00	1.52E-01	−90.0	9.04E-02	−94.1	1.37E-01	−91.0

Table 12

Environmental and energy assessment of the improved national transportation scenarios per FU (1 kg) of cauliflower. Comparing impacts and savings associated with the replacement of national distribution (500 km) with diesel trucks with international distribution (2500 km) by trucks using different fuel options (diesel, hybrid or compressed natural gas-CNG) or using multimodal transport (diesel truck and train).

Impact category	Units	National	International							
		Diesel	Diesel		Hybrid		CNG		Multimodal	
		Impact	Impact	%savings	Impact	%savings	Impact	%savings	Impact	%savings
Climate change	kg CO_2eq	9.40E-02	4.64E-01	+79.8	2.35E-01	+60.0	2.16E-01	+54.5	2.74E-01	+65.7
Photochemical ozone formation	kg NMVOC eq	2.78E-04	1.37E-03	+79.8	1.15E-03	+75.9	8.56E-04	+60.0	2.14E-03	+87.0
Acidification	mol H+ eq	3.06E-04	1.51E-03	+79.8	1.44E-03	+78.7	8.15E-04	+53.3	1.84E-03	+83.4
Eutrophication, freshwater	kg P eq	6.94E-06	3.43E-05	+79.8	1.22E-04	+94.3	3.97E-05	+76.2	2.75E-05	+74.8
CED	MJ	1.52E+00	7.51E+00	+79.8	4.47E+00	+66.0	6.77E+00	+62.9	4.20E+00	+63.8

Concerning the advanced scenarios for the fresh cauliflower, the main conclusions are:

a) The substitution of the single-use carboard box with a reusable plastic crate was the most effective decision to reduce the CF and improve the environmental and energy performance of the post-harvest stage of the fresh vegetable. This is due to the benefits of using reusable packaging elements and the strong contribution of the single-use components to the overall environmental performance of the post-harvest stage. It was also observed that the environmental burden of the brassicas mix was significantly higher than that of the cauliflower due to overpackaging of the former. Hence, the use of excessive packaging should be avoided as much as possible if there is no loss of quality in the fresh vegetable product. Increased use of recycled material or improving its recyclability in its EoL contributes, to a lesser extent, to the environmental performance of the packaging stage.

b) Related to transport, there is a direct relationship between environmental footprint and distance, local consumption is always recommended. In all cases, CNG and hybrid (electricity-diesel) vehicles represent a more sustainable alternative to conventional diesel-powered trucks. When long distance is demanded, multimodal transport by rail is a more environmentally friendly alternative to road transport. This fact highlights European transport rail corridors as being essential planning elements to ensure territorial cohesion, economic efficiency, and a sustainable environment among vegetable-producing areas and international markets, contributing to reducing the CF in the overall food chain.

c) Whilst the use of renewable energy in the processing factory reduced the CF of this stage, the benefit in the post-harvest stage of the products was scant due to its limited overall contribution.

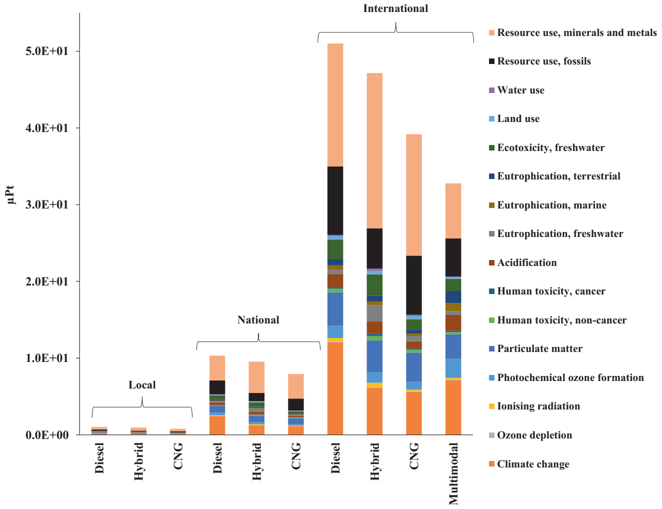


Fig. 10. Environmental single score indicator for different transport scenarios (distance range and technology) per FU (1 kg) of cauliflower.

d) The application of advanced strategies for the management of organic residues (generation of biogas or their utilization for animal feed) contribute to improving the environmental performance of the post-harvest stage of fresh vegetable products. However, the overall impact of these activities remains scarce due to its limited contribution.

Finally, to save energy and minimize the environmental burdens associated with the post-harvest stage of fresh vegetable products, it should be recommended that efforts be focused on the use of reusable packaging materials; avoiding over packaging; reducing the distance range (prioritize local consumption), the use of improved transportation technologies (CNG or hybrid-powered vehicles) and the use of multimodal rail transport wherever possible for longer distances.

This study has the limitation that it only focused on the environmental and energy footprint of these scenarios; to improve this work, the economic and social impacts should be associated with these environmental decisions.

CRediT authorship contribution statement

Laura Rasines: Experiments, Data curation, Methodology, Software, Writing – original draft preparation. **Guillermo San Miguel:** Conceptualization, Methodology, Supervision, Validation, Writing - review & editing. **Ángel Molina:** Conceptualization, Methodology and Supervision. **Francisco Artés-Hernández, Eloy Hontoria:** Conceptualization, Visualization. **Encarna Aguayo:** Conceptualization, Data curation, Supervision, Writing - review & editing, Funding acquisition Project administration.

Data availability

Data will be made available on request.

Declaration of 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.

Acknowledgments

This research was funded by RTI2018-099139-B-C21 from Spanish Ministry of Science and Innovation - National Research Agency (MCIN/AEI/10.13039/501100011033) and by "ERDF A way of making Europe", of the "European Union". Laura Rasines acknowledges financial support for PRE 2019-090573 grant by MCIN/AEI and by "ESF Investing in your future".

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.160422.

References

AGROPAL, 2021. Fertilizantes nitrogenados sólidos. https://www.agropalsc.com/productos_agricultura_des.shtml?idboletin=1085. (Accessed 2 February 2021).

Anand, S., Gupta, A., Tyagi, S.K., 2014. Critical analysis of a biogas powered absorption system for climate change mitigation. Clean Techn. Environ. Policy 16, 569–578. https://doi.org/10.1007/s10098-013-0662-y.

Ashnani, M.H.M., Miremadi, T., Johari, A., Danekar, A., 2015. Environmental impact of alternative fuels and vehicle technologies: a life cycle assessment perspective. Procedia Environ. Sci. 30, 205–210. https://doi.org/10.1016/j.proenv.2015.10.037.

Bartzas, G., Zaharaki, D., Komnitsas, K., 2015. Life cycle assessment of open field and greenhouse cultivation of lettuce and barley. Inf. Process. Agric. 2, 191–207. https://doi.org/10.1016/j.inpa.2015.10.001.

Benedik, N., Keller, M., Cox, B., 2019. Handbook Emission Factors for Road Transport 4.1, pp. 1–151.

Bengoa, X., Chappuis, C., Guignard, C., Liernur, A., Kounina, A., Papadimitriou, C., Rossi, V., Bayart, J.-B., 2019. World Food LCA Database Documentation. Version 3.5, November 2019. Quantis, Lausanne, Switzerland.

Boschiero, M., Zanotelli, D., Ciarapica, F.E., Fadanelli, L., Tagliavini, M., 2019. Greenhouse gas emissions and energy consumption during the post-harvest life of apples as affected by storage type, packaging and transport. J. Clean. Prod. 220, 45–56. https://doi.org/10.1016/j.jclepro.2019.01.300.

Canals, L.M.I., Muñoz, I., Hospido, A., Plassmann, K., McLaren, S., 2008. Life Cycle Assessment (LCA) of domestic vs. imported vegetables. Case studies on broccoli, salad crops and green beans. United Kingdom, Cent. Environ. Strateg. Univ. Surrey. 46 doi:1464-8083.

Cherubin, M.R., Oliveira, D.M.D.S., Feigl, B.J., Pimentel, L.G., Lisboa, I.P., Gmach, M.R., Varanda, L.L., Morais, M.C., Satiro, L.S., Popin, G.V., De Paiva, S.R., Dos Santos, A.K.B., De Vasconcelos, A.L.S., De Melo, P.L.A., Cerri, C.E.P., Cerri, C.C., 2018. Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: a review. Sci. Agric. 75, 255–272. https://doi.org/10.1590/1678-992x-2016-0459.

Colley, T.A., Birkved, M., Olsen, S.I., Hauschild, M.Z., 2020. Using a gate-to-gate LCA to apply circular economy principles to a food processing SME. J. Clean. Prod. 251, 119566. https://doi.org/10.1016/j.jclepro.2019.119566.

Colomb, V., Amar, S., Basset-Mens, C., Gac, A., Gaillard, G., Koch, P., Mousset, J., Salou, T., Tailleur, A., van der Werf, H., 2014. AGRIBALYSE®, the french LCI database for agricultural products: high quality data for producers and environmental labelling. OCL - Ol. Corps Gras Lipides 22, D104. https://doi.org/10.1051/ocl/20140047.

Demichelis, F., Piovano, F., Fiore, S., 2019. Biowaste management in Italy: challenges and perspectives. Sustain. 11. https://doi.org/10.3390/su11154213.

Durlinger, B., Tyszler, M., Scholten, J., Broekema, R., Blonk, H., 2014. Agri-Footprint: A Life Cycle Inventory database covering food and feed production and processing. 9th International Conference LCA of Food: San Francisco, USA. American Center for Life Cycle Assessment, pp. 310–317 8–10 October.

Environdec, 2020. Product Category Rules for Arable and Vegetable Crops, pp. 1–30.

Eriksson, M., Strid, I., Hansson, P.A., 2015. Carbon footprint of food waste management options in the waste hierarchy - a swedish case study. J. Clean. Prod. 93, 115–125. https://doi.org/10.1016/j.jclepro.2015.01.026.

ESU Services, 2021. ESU world food LCA database [WWW Document]. https://esu-services.ch/data/fooddata/ accessed 10.12.20.

FAO, 2018. The future of food and agriculture – Alternative pathways to 2050. Summary version. Rome, p. 60. https://www.fao.org/3/CA1553EN/ca1553en.pdf. (Accessed 2 February 2021).

FAO, 2021. Food and Agriculture Organization Corporate Statistical Database (FAOSTAT). https://www.fao.org/faostat/en/#data/FBS. (Accessed 2 February 2021).

Fazio, S., Castellani, V., Sala, S., Schau, E.M., Secchi, M., Zampori, L., Diaconu, E., 2018. Supporting information to the characterisation factors of recommended EF life cycle impact assessment methods. Ilcd. https://doi.org/10.2760/002447.

Ferguson, J.D., 2019. Food residue, loss and waste as animal feed. Encyclopedia of Renewable and Sustainable Materials. Elsevier Ltd. https://doi.org/10.1016/b978-0-12-803581-8.11169-5.

Frischknecht, R., Editors, N.J., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Hischier, R., Hellweg, S., Köllner, T., Loerincik, Y., Margni, M., 2007. Implementation of Life Cycle Impact Assessment Methods. Am. Midl. Nat 150, 1–151.

Girotto, F., Alibardi, L., Cossu, R., 2015. Food waste generation and industrial uses: a review. Waste Manag. 45, 32–41. https://doi.org/10.1016/j.wasman.2015.06.008.

Gustafsson, M., Svensson, N., Eklund, M., Oberg, J.D., 2021. Well-to-wheel Greenhouse Gas Emissions of Heavy-duty Transports: Influence of Electricity Carbon Intensity. 93.

Hischier, R., Classen, M., Lehmann, M., Scharnhorst, W., 2007. Swiss Centre for Life Cycle inventories (Ecoinvent v2.0): Part ll: Modules. 0. Swiss Cent. Life Cycle Invent. (Ecoinvent v2.0), p. 116.

Hwang, Y., 2004. Potential energy benefits of integrated refrigeration system with microturbine and absorption chiller. Int. J. Refrig. 27, 816–829. https://doi.org/10.1016/j.ijrefrig.2004.01.007.

Ingwersen, W.W., 2012. Life cycle assessment of fresh pineapple from Costa Rica. J. Clean. Prod. 35, 152–163. https://doi.org/10.1016/j.jclepro.2012.05.035.

Iriarte, A., Yáñez, P., Villalobos, P., Huenchuleo, C., Rebolledo-Leiva, R., 2021. Carbon footprint of southern hemisphere fruit exported to Europe: the case of chilean apple to the UK. J. Clean. Prod. 293. https://doi.org/10.1016/j.jclepro.2021.126118.

ISO, 2006. ISO 14040: Environmental Management e Life Cycle Assessment e Principles and, Framework.

ISO, 2006. ISO 14044: Environmental Management e Life Cycle Assessment e Requirements and Guidelines.

ISO-UNE ISO 50001, 2018. Norma Española UNE-ISO 50001-2018: Requisitos con orientación para su uso. 47.

Jørgensen, P.J., 2009. Biogas green energy. Environ. Energy 2, 27.

Keng, Z.X., Chong, S., Ng, C.G., Ridzuan, N.I., Hanson, S., Pan, G.T., Lau, P.L., Supramaniam, C.V., Singh, A., Chin, C.F., Lam, H.L., 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.

Kim, M.H., Kim, J.W., 2010. Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global warming and resource recovery. Sci. Total Environ. 408, 3998–4006. https://doi.org/10.1016/j.scitotenv.2010.04.049.

Leonidas, N., Zissis, S., 2019. EEA Road transport 2019. 53, pp. 1689–1699.

Li, Y., Manandhar, A., Li, G., Shah, A., 2018. Life cycle assessment of integrated solid state anaerobic digestion and composting for on-farm organic residues treatment. Waste Manag. 76, 294–305. https://doi.org/10.1016/j.wasman.2018.03.025.

Li, Y., Wen, Z., Li, J., Cai, L., Wang, H., 2019. Feasibility of utilizing by-product biogas in breweries after being decarbonized for refrigeration chiller and related primary energy efficiency analysis. Sustain. Energy Technol. Assess. 31, 390–400. https://doi.org/10.1016/j.seta.2019.01.001.

Liu, Y., Langer, V., Høgh-Jensen, H., Egelyng, H., 2010. Life cycle assessment of fossil energy use and greenhouse gas emissions in chinese pear production. J. Clean. Prod. 18, 1423–1430. https://doi.org/10.1016/j.jclepro.2010.05.025.

López-Gálvez, F., Rasines, L., Perla, A.G., Artés-Hernández, F., Aguayo, E., 2021. Reusable plastic crates (RPCs) for fresh produce (case study on cauliflowers): sustainable packaging but potential salmonella survival and risk of cross-contamination. Foods 10, 1–17.

Manfredi, S., Allacker, K., Chomkhamsri, K., Pelletier, N., Maia de Souza, D., 2012. Product Environmental Footprint (PEF) Guide. Deliverable 2 and 4A of the Administrative Arrangement Between DG Environment and the Joint Research Centre No N 070307/2009/552517, Including Amendment No 1 From December 2010.

MAPA, 2021a. Cifras del sector de Frutas y Hortalizas. https://www.mapa.gob.es/es/agricultura/temas/producciones-agricolas/cifrasdelsectorfyhactualizado2020definitivo-junio2021_tcm30-563965.pdf. (Accessed 10 January 2021).

MAPA, 2021b. Superficies y producciones anuales de cultivos. https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/superficies-producciones-anuales-cultivos/. (Accessed 10 January 2021).

Maraseni, T.N., Mushtaq, S., Reardon-Smith, K., 2012. Integrated analysis for a carbon- and water-constrained future: an assessment of drip irrigation in a lettuce production system in eastern Australia. J. Environ. Manag. 111, 220–226. https://doi.org/10.1016/j.jenvman.2012.07.020.

Marcello, B., Di Gennaro, V., Ferrini, S., 2021. Let the citizens speak: an empirical economic analysis of domestic organic waste for community composting in Tuscany. J. Clean. Prod. 306, 127263. https://doi.org/10.1016/j.jclepro.2021.127263.

Martin-Gorriz, B., Soto-García, M., Martínez-Alvarez, V., 2014. Energy and greenhouse-gas emissions in irrigated agriculture of SE (southeast) Spain. Effects of alternative water supply scenarios. Energy 77, 478–488. https://doi.org/10.1016/j.energy.2014.09.031.

Martin-Gorriz, B., Gallego-Elvira, B., Martínez-Alvarez, V., Maestre-Valero, J.F., 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.

Mbow, C., Rosenzweig, C., Barioni, L.G., Benton, T.G., Herrero, M., Krishnapillai, M., Liwenga, E., Pradhan, P., Rivera-Ferre, M.G., Sapkota, T., Tubiello, F.N., Xu, Y., 2019. Food security. Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Food Secur. Clim. Chang. L. an IPCC Spec. Rep. Clim. Chang. Desertif. L. Degrad. Sustain. L. Manag. food Secur. Greenh. gas fluxes Terr. Ecosyst.

MITECO, 2019. Memoria anual de generación y gestión de residuos. https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/publicaciones/Memoria-anual-generacion-gestion-residuos.aspx. (Accessed 10 May 2020).

NREL, 2021. System Advisor Model (SAM). https://sam.nrel.gov/. (Accessed 12 May 2021).

Oosterkamp, W.J., 2020. Use of volatile solids from biomass for energy production. Recent Developments in Bioenergy Research. BV https://doi.org/10.1016/b978-0-12-819597-0.00006-4.

Papargyropoulou, E., Lozano, R., Steinberger, K., Wright, J., Ujang, N., Bin, Z., 2014. The food waste hierarchy as a framework for the management of food surplus and food waste. J. Clean. Prod. 76, 106–115. https://doi.org/10.1016/j.jclepro.2014.04.020.

Parajuli, R., Matlock, M.D., Thoma, G., 2021. Cradle to grave environmental impact evaluation of the consumption of potato and tomato products. Sci. Total Environ. 758, 143662. https://doi.org/10.1016/j.scitotenv.2020.143662.

Payen, S., Basset-Mens, C., Perret, S., 2015. LCA of local and imported tomato: an energy and water trade-off. J. Clean. Prod. 87, 139–148. https://doi.org/10.1016/j.jclepro.2014.10.007.

Peano, C., Baudino, C., Tecco, N., Girgenti, V., 2015. Green marketing tools for fruit growers associated groups: application of the life cycle assessment (LCA) for strawberries and berry fruits ecobranding in northern Italy. J. Clean. Prod. 104, 59–67. https://doi.org/10.1016/j.jclepro.2015.04.087.

Pereira, B.D.J., Bernardes, A., Filho, C., La Jr., N., S., 2021. Greenhouse gas emissions and carbon footprint of cucumber, tomato and lettuce production using two cropping systems. J. Clean. Prod. 282, 124517. https://doi.org/10.1016/j.jclepro.2020.124517.

Persiani, A., Diacono, M., Monteforte, A., Montemurro, F., 2019. Agronomic performance, energy analysis, and carbon balance comparing different fertilization strategies in horticulture under Mediterranean conditions. Environ. Sci. Pollut. Res. 26, 19250–19260. https://doi.org/10.1007/s11356-019-05292-x.

Ponsioen, T., Nuhoff-isakhanyan, G., Vellinga, T., Baltussen, W., Boone, K., Woltjer, G., 2020. Monetisation of sustainability impacts of food production and consumption. Wageningen Econ. Res. 1–24.

Prasad, S., Singh, A., Korres, N.E., Rathore, D., Sevda, S., Pant, D., 2020. Sustainable utilization of crop residues for energy generation: a life cycle assessment (LCA) perspective. Bioresour. Technol. 303, 122964. https://doi.org/10.1016/j.biortech.2020.122964.

PRé Consultant, 2021. SimaPro | The world's leading LCA software. https://simapro.com/ (accessed 10.2.21.

Rana, R.L., Andriano, A.M., Giungato, P., Tricase, C., 2019. Carbon footprint of processed sweet cherries (Prunus avium L.): from nursery to market. J. Clean. Prod. 227, 900–910. https://doi.org/10.1016/j.jclepro.2019.04.162.

Ravigné, E., Da Costa, P., 2021. Economic and environmental performances of natural gas for heavy trucks: a case study on the french automotive industry supply chain. Energy Policy 149. https://doi.org/10.1016/j.enpol.2020.112019.

REE, 2021. Red Eléctrica de España. https://www.ree.es/es/datos/publicaciones/informe-anual-sistema/informe-del-sistema-electrico-espano. (Accessed 1 February 2021).

Rial, M., Javier, P., 2021. Transportation Research Interdisciplinary Perspectives Environmental Performance of Four Different Heavy-duty Propulsion Technologies Using Life Cycle Assessment. 11. https://doi.org/10.1016/j.trip.2021.100428.

Rojo, E., Carmona, A., Soto, C., Díaz, I., Fernández-Polanco, M., Palacio, L., Muñoz, R., Bolado, S., 2021. Environment and material science technology for anaerobic digestion-based circular bioeconomy. Biomass, Biofuels, Biochem. 25–55. https://doi.org/10.1016/B978-0-12-821878-5.00024-6.

Romero-Gámez, M., Audsley, E., Suárez-Rey, E.M., 2014. Life cycle assessment of cultivating lettuce and escarole in Spain. J. Clean. Prod. 73, 193–203. https://doi.org/10.1016/j.jclepro.2013.10.053.

Rothwell, A., Ridoutt, B., Page, G., Bellotti, W., 2016. Environmental performance of local food: trade-offs and implications for climate resilience in a developed city. J. Clean. Prod. 114, 420–430. https://doi.org/10.1016/j.jclepro.2015.04.096.

Salemdeeb, R., Zu Ermgassen, E.K.H.J., Kim, M.H., Balmford, A., Al-Tabbaa, A., 2017. Environmental and health impacts of using food waste as animal feed: a comparative analysis of food waste management options. J. Clean. Prod. 140, 871–880. https://doi.org/10.1016/j.jclepro.2016.05.049.

San Miguel, G., Corona, B., 2018. Economic viability of concentrated solar power under different regulatory frameworks in Spain. Renew. Sust. Energ. Rev. 91, 205–218. https://doi.org/10.1016/j.rser.2018.03.017.

Svanes, E., Johnsen, F.M., 2019. Environmental life cycle assessment of production, processing, distribution and consumption of apples, sweet cherries and plums from conventional agriculture in Norway. J. Clean. Prod. 238. https://doi.org/10.1016/j.jclepro.2019.117773.

Syed, A., Mierlo, J.Van, Messagie, M., 2019. Life cycle assessment of electrification of heavy-duty vehicle. 32nd Electr. Veh. Symp. Lyon, Fr. May 19 - 22, 2019, pp. 1–12.

USDA, 2021. FoodData central. https://fdc.nal.usda.gov/index.html. (Accessed 10 January 2021).

Wolfram, P., Wiedmann, T., 2017. Electrifying australian transport : hybrid life cycle analysis of a transition to electric light-duty vehicles and renewable electricity. Appl. Energy 206, 531–540. https://doi.org/10.1016/j.apenergy.2017.08.219.

Zakeri, B., Cross, S., Dodds, P.E., Castagneto, G., 2021. Policy options for enhancing economic profitability of residential solar photovoltaic with battery energy storage. Appl. Energy 290, 116697. https://doi.org/10.1016/j.apenergy.2021.116697.

Zampori, L., Pant, R., 2019. Suggestions for Updating the Product Environmental Footprint (PEF) Method, Eur 29682 En. https://doi.org/10.2760/424613.