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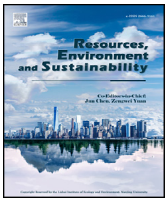

Reseach article

Environmental impact assessment of producing frozen spinach in central Italy

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ABSTRACT

Europe has increased its production, processing, and export of vegetables in recent decades due to changing dietary patterns supporting a greater consumption of vegetables high in nutrition. The growing interest in environmental issues has led to advocacy for sustainable vegetable production and consumption. Thus, this study assessed the ecological impacts of producing 1 kg of frozen spinach (functional unit) by a food processor in central Italy (cradle-to-factory gate approach). We evaluated the global warming potential (GWP) for distributing the final to different destinations. We also compare the potential environmental credits for different spinach residue management strategies, residue reduction through improved process efficiency, and as a feedstock for biogas production (avoided maize silage) based on the total volatile solids content. The life cycle assessment was used following the CML_IA impact assessment method based mainly on primary data related to 2019/2020. The GWP was 1.55 kg CO_2eq. with respect to the functional unit. Excluding the dominant cultivation phase, packaging, particularly corrugated board boxes, electricity, and wastewater treatment were significant contributors across the midpoint impact categories assessed. The GWP for distributing the packaged frozen to Australia was 24 times more impactful than regional inland distribution. When spinach residue is reduced to 20% and 10%, total impacts for all impact categories also decrease by 12% and 22%, respectively. The benefit of using the current amount of spinach residue to produce biomethane was less than 7% across all impact categories except terrestrial ecotoxicity (13%). Therefore, reducing spinach waste along the processing line and efficient end-of-packaging life management through recycling and reuse by the manufacturer can considerably reduce the environmental impacts of frozen spinach.

1. Introduction

The stable growing market for vegetables in Europe has increased production levels over the past decade. Various reasons, including health, environmental, religious, and ethical concerns, account for the changing diet toward higher consumption of vegetables (Ruby, 2012; Hargreaves et al., 2021). However, this sector's primary challenge is the high postharvest losses incurred along the supply chain with substantial environmental and economic consequences (Iordachescu et al., 2019). Freezing vegetables prove to be a viable alternative to increasing the shelf-life and reducing food loss (Sridhar et al., 2021). Generally, vegetables have comparatively low environmental impacts than other food commodities (Ruini et al., 2015). However, the high production volume of vegetables and various postharvest operations make their ecological impact notable. Although the market for frozen vegetables is expanding, few impact assessment studies exist in this sector. There is a need to assess the environmental sustainability of these products to highlight hotspots for improvements while filling the present research gaps.

The European Union is the world's largest producer and importer of frozen vegetables, with about 90% of trade activities occurring within the region. Between 2014 and 2018, the volume of imported frozen vegetables increased annually by about 3% (Centre for the Promotion of Imports from developing countries , CBI). The market for frozen vegetables was valued at $3.3 billion in 2018, corresponding to 3.4 million tonnes (Centre for the Promotion of Imports from developing countries , CBI). Increasing consumer preference for “ready to eat” or “easy to prepare” foods is one of the main drivers for the growth of this market. In Italy, the sale of frozen vegetables increased from approximately 228,000 tons in 2019 to 252,000 tons in 2020 (Istituto Italiano Alimenti Surgelati, 2021). Frozen vegetables are prepared by freezing fresh vegetables to about -18 °C at the core. Vegetables also undergo several operations, including washing, peeling, grading, cutting, blanching, and packaging before freezing.

An essential aspect of frozen products, including vegetables, is environmental sustainability due to increasing awareness of the threats of climate change (Ilari et al., 2019; Ríos-Fuentes et al., 2022). The current

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European Green Deal outlines strategies targeting no net emissions of greenhouse gases (GHG) in the EU by 2050 (European Commission, 2019). Agriculture is responsible for about a third of global greenhouse gas emissions. Reducing the carbon footprints of agricultural and food supply chains is central to limiting climate change (Gilbert, 2012). The GHG emissions are often associated with the production phase due to the high use of agrochemicals like fertilizers, pesticides, and herbicides (Yue et al., 2017). However, GHG emissions can be mitigated at various points along the supply chain from producers, processors, distributors, retailers, and consumers. Due to environmental awareness, more consumers are willing to significantly decrease meat consumption and increase vegetable intake to reduce GHG emissions (Sanchez-Sabate and Sabaté, 2019). Thus, there is a need to streamline operations along vegetable supply chains to improve environmental performance and encourage consumption.

Sustainability certification schemes are gaining popularity in the agri-food sector, fueled by the growing interest of retailers and consumers in the environmental performance of food products (Ge and Brewster, 2016). Ecological sustainability is an essential issue in frozen food products as it indicates how products or activities affect protective goods, like soil, water, air, and climate (Trapp et al., 2017). Products displaying sustainability certifications such as reduced CO_2 emissions, recyclable packaging, and organic and pesticide-free products emphasize food production and processing under sustainable strategies and methods. An accurate assessment of the environmental footprints of frozen vegetables has become necessary due to the large number and intricate operations within their systems (Alhashim et al., 2021). The life cycle assessment (LCA) is a widespread standardized method that provides quantitative and qualitative analysis of a product's environmental performance over its life cycle (Curran, 2012). Its application in the agri-food sector is fast-growing due to its ability to highlight environmental hotspots for improvements along the food production and supply chains (Stillitano et al., 2021). With the surging demand for ecological sustainability certification schemes in the horticultural sector, the LCA can prove helpful to food manufacturers in improving their sustainability metrics.

Spinach (*Spinacia oleracea* L.) is a widely consumed versatile leafy vegetable of high nutritional quality (Morelock et al., 2008). Fresh spinach is a perishable vegetable with about two weeks of shelf-life, necessitating freezing as a viable option for shelf-life extension. Frozen spinach is of interest to most consumers due to its prolonged shelf-life, availability, safety, and convenience in preparation and handling. Frozen spinach shows comparable Vitamin C content to freshly harvested spinach (Favell, 1998; Dermesonluoglu et al., 2015). The freezing process minimally impacts quality parameters such as color, texture, and sensory attributes. Italy is the current leading spinach producer in Europe, with an estimated 100,000 tons in 2020 (FAOSTAT, 2022). Spinach produced in Italy is sold as fresh, frozen whole leaves or cut frozen leaves in various shapes at retail shops. The typical supply chain of spinach in Italy often involves pre-harvest operations such as land selection, variety selection, cultivation, harvesting, and postharvest operations that include cooling/freezing, packaging, transporting, storage, use, and waste disposal (Pedretti et al., 2021).

Environmental impact assessments in the fruit and vegetable sector mainly target fresh produce, emphasizing the cultivation step (Ilari et al., 2019; Canals et al., 2008). In the context of spinach, studies show low global warming potential (GWP) in the range of 0.075 to 0.50 kg CO_2 eq./kg of fresh spinach for the cultivation phase, with organic cultivation generally recording lower impacts (Pedretti et al., 2021; Theurl et al., 2017; Seo et al., 2017). Some studies also considered other postharvest processing activities, such as washing, packaging, cooling, storage, and distribution, and reported higher GWP levels of up to 2.3 kg CO_2 eq./kg spinach (Stoessel et al., 2012; Frankowska et al., 2019; Shiina et al., 2011). However, no LCA study focused solely on frozen spinach at the manufacturing level. Studies on the environmental impact assessment of frozen and canned spinach are rare and mostly rely on secondary and tertiary data on a national or regional level, with potentially huge variabilities and uncertainties within the data pool (Trapp et al., 2017). This limits the potential for identifying specific mitigation strategies for value chain actors along the production chain. Therefore, this study aims to evaluate the environmental performance of frozen spinach production by a consortium in central Italy based on a cradle-to-factory gate approach. The results are targeted at helping manufacturers of frozen vegetables to improve their environmental sustainability. Additionally, this study could also represent the first point of reference for a burgeoning but little-known sector. The results from the study could also support decisions regarding sourcing fresh vegetables, means of transportation, and packaging choices.

2. Methodology

We performed the life cycle assessment (LCA) to calculate the impacts of 1 kg of minimally processed frozen spinach, following the ISO 14040/14044 standards (ISO, 2006a,b). LCA is a standardized methodology for assessing potential environmental impacts associated with a product, a process, or a system, along its life cycle, usually from raw material extraction to the end of life (Sala et al., 2016). LCA consists of four interrelated phases, generally completed in the following order: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation. LCA is an iterative process where the different phases can be repeated until the set objective has been reached. The same standards state that the analysis can stop at any life cycle stage with an appropriate justification. This attributional LCA study's methodology, data, and assumptions are detailed in the following sections.

2.1. Case study: Brief description of the company

The primary data analyzed in this study came from an Italian agricultural joint-stock consortium involved in growing and selling minimally processed frozen vegetables. The company operates in domestic and export markets and is engaged in business-to-business (B-2-B) and business-to-consumer (B-2-C) commerce transactions in different market segments. The food processor produces and sells frozen vegetables for the food industry and retailers (supermarkets) and is a major supplier to some giant frozen vegetable producers in Italy. The company contributes about 5% of Italy's total national spinach production and produces over 6500 tonnes of leaf products like spinach, chicory, and chard annually. Over 80 local spinach producers are registered as members of the joint-stock consortium from different regions in Italy's central and southern parts. The farmers cultivate spinach mainly under the integrated farming system (93%) and organic farming system.

2.2. Goal and scope

Our attributional LCA study aims to calculate the environmental impacts associated with a medium-scale Italian vegetable processor involved in the processing and distribution of frozen spinach and identify the main contributors within the production chain. This will help establish baseline information on the manufacturer's activities and support initiatives for future product certification for environmental sustainability. We also aim to elaborate and provide a consistent and up-to-date life cycle inventory (LCI) of a typical frozen spinach production chain in Italy. The study focuses mainly on the processing and distribution phase, as impacts relative to the cultivation phase have already been extensively reported in a previous study (Pedretti et al., 2021). The function of the product system is to provide frozen spinach as a minimally processed food ingredient to other food processing companies and food business owners. This includes spinach cultivation under integrated and organic farming systems and all postharvest activities leading to the processing of the fresh spinach into packaged frozen spinach ready for distribution.

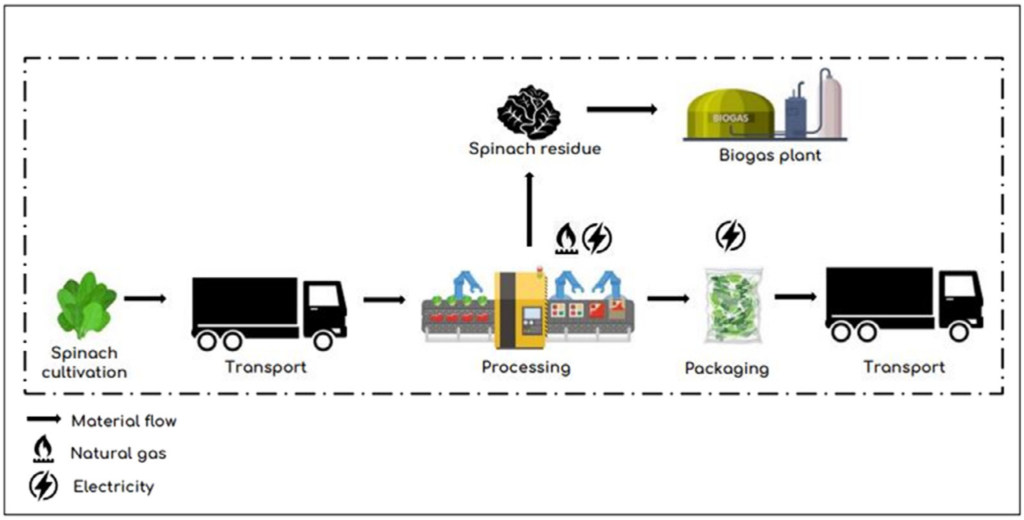

Fig. 1. The system boundary of the phases considered for frozen spinach production (dotted lines).

The chosen functional unit (FU), based on which the inventory data was normalized for assessing the impacts in this study, was 1 kg of frozen spinach, excluding the packaging weight. About 30% of the fresh spinach is lost during processing. For this reason, we calculated a reference flow of 1.42 kg of fresh spinach from the farms, which means 1.42 kg of fresh spinach is needed to produce 1 kg of frozen spinach. We assumed no losses during transportation since the loading capacity was 50%, and processing was carried out on the same day of harvesting to prevent quality loss.

2.2.1. System boundary

The system boundary encompasses the energy and material inputs/outputs related to producing packaged frozen spinach, as shown in Fig. 1. The various phases within the supply chain under study are detailed below. However, input data on cleaning agents associated with the processing phase were excluded since the food processor indicated that no cleaning agents were used directly on the processing lines.

2.2.2. Limitation

This LCA study follows a "cradle-to-factory gate" approach and does not include some downstream phases, such as retail storage, consumer transportation, product use, and end-of-packaging life. We excluded the construction and maintenance of the processing facility and the transport of input materials, such as packaging. This is due to the lack of primary data, as those phases are outside the company's direct management. Additionally, many possible scenarios can be assumed, making it challenging to model and compare results.

2.3. System description and life cycle inventory

2.3.1. Cultivation

The cultivation stage was duly assessed in a previous paper (Pedretti et al., 2021), in which an LCA for integrated and organic spinach farming was performed. The fresh spinach for the company was cultivated in several regions in central and southern parts of Italy, namely, Emilia-Romagna, Marche, Lazio, Umbria, Puglia, and Molise. The spinach was grown on open fields using standard agricultural practices. The farmers carried out land preparation activities such as tillage operations like plowing and harrowing before sowing. Seedbed preparation involved disk plowing followed by rolling with the appropriate spacing, as spinach seeds require a finely manicured, firm, and level seedbed. The farmers used two different cultivation systems: organic farming and integrated farming. The main differences were the application and use of synthetic fertilizers, pesticides, and herbicides for cultivation. Irrigation was also performed using sprinkler and furrow systems. In this study, the primary data for the cultivation was a mass-based average of the spinach grown under both systems, with the integrated spinach accounting for 93% of the total spinach transported to the processing facility.

2.3.2. Transport to factory

Once harvested, spinaches are immediately transported to the company's gate, and the processing is carried out on the same day. Third-party companies oversee the transport of the spinach to the factory. Generally, the spinach cultivated in the Marche region is transported by trucks with a payload of 11 tons, whiles spinach from other areas is transported by articulated trucks with 23 tons of load. These transport means are opened at the top to avoid spinach fermentation. Integrated spinach is cultivated in farms in the central and southern regions located between 55 km and 411 km from the processing facility. Organic spinach is solely grown in Cerignola in the Puglia region, which is 411 km by road from the processing plant. The trucks are powered by diesel with a load factor of 50% because spinaches have a low density and compressive strength. The trucks are empty for the return journey because they are solely dedicated to transporting fresh vegetables. We considered the amount of spinach, transport mean, load factor, and distance between the farmer and the processing facility of each producer in calculating the impacts from the transportation phase. Transport input data on the farm location, payload by distance, and transport means are detailed in Table 1.

2.3.3. Spinach processing

As depicted in Fig. 2, the fresh spinach undergoes a series of minimal operations to yield the final packaged frozen product. The first three-unit processes are separators (sand trap, pneumatic separator, and optical separator), which work depending on different discriminatory agents. The sand trap removes sand, stones, and insects from the spinach, the pneumatic separator removes heavy particles like stones, stems, and ground, and the optical separator sorts out the defective spinach according to color. All the organic wastes produced from this step are sent to a biogas plant for waste management. Afterward, the spinach is washed at two-unit processes (fluctuation and decantation). Water is drawn from wells and subjected to a purification process in both washing unit processes.

The spinach is cooked after washing in a multiphase cooker composed of four steps with different temperatures. The section temperatures are 75 °C (pre-heating), 90 °C (heating), 80 °C (pre-cooling), and 23 °C (cooling of the product). A visual inspection is performed, and

Table 1
Transportation details on fresh spinach supply from the farms to the factory.

Town	Province	Region	Transport (farm to factory) t-km	Transport means
Ravenna	Ravenna	Emilia Romagna	7677.18	Truck (>20t, Euro 3, 50% LF)
Latina	Latina	Lazio	25367.04	Truck (>20t, Euro 3, 50% LF)
Casette d'Ete	Fermo	Marche	15966.76	Truck ((10–20t, Euro 3, 50% LF)
Corridonia	Macerata	Marche	12112.32	Truck ((10–20t, Euro 3, 50% LF)
Girola di Fermo	Fermo	Marche	2024.67	Truck ((10–20t, Euro 3, 50% LF)
Morrovalle	Macerata	Marche	42417.07	Truck ((10–20t, Euro 3, 50% LF)
Osimo	Ancona	Marche	20782.30	Truck ((10–20t, Euro 3, 50% LF)
Paludi di Fermo	Fermo	Marche	848.782	Truck ((10–20t, Euro 3, 50% LF)
Piane di Rapagnano	Fermo	Marche	3770.33	Truck ((10–20t, Euro 3, 50% LF)
Potenza Picena	Macerata	Marche	9284.40	Truck ((10–20t, Euro 3, 50% LF)
Recanati	Macerata	Marche	24380.22	Truck ((10–20t, Euro 3, 50% LF)
S. Elpidio a mare	Fermo	Marche	15025.74	Truck ((10–20t, Euro 3, 50% LF)
Tolentino	Macerata	Marche	10027.04	Truck ((10–20t, Euro 3, 50% LF)
Villa Potenza	Macerata	Marche	10167.69	Truck ((10–20t, Euro 3, 50% LF)
Larino	Campobasso	Molise	36148.32	Truck (>20t, Euro 3, 50% LF)
Ascoli Satriano	Foggia	Puglia	154203.09	Truck (>20t, Euro 3, 50% LF)
Cerignola	Foggia	Puglia	337536.60	Truck (>20t, Euro 3, 50% LF)
Foggia	Foggia	Puglia	80291.25	Truck (>20t, Euro 3, 50% LF)
Serra Capriola	Foggia	Puglia	137385.60	Truck (>20t, Euro 3, 50% LF)
Beroide-Spoleto	Perugia	Umbria	25128.00	Truck (>20t, Euro 3, 50% LF)
Foligno	Perugia	Umbria	9335.04	Truck (>20t, Euro 3, 50% LF)

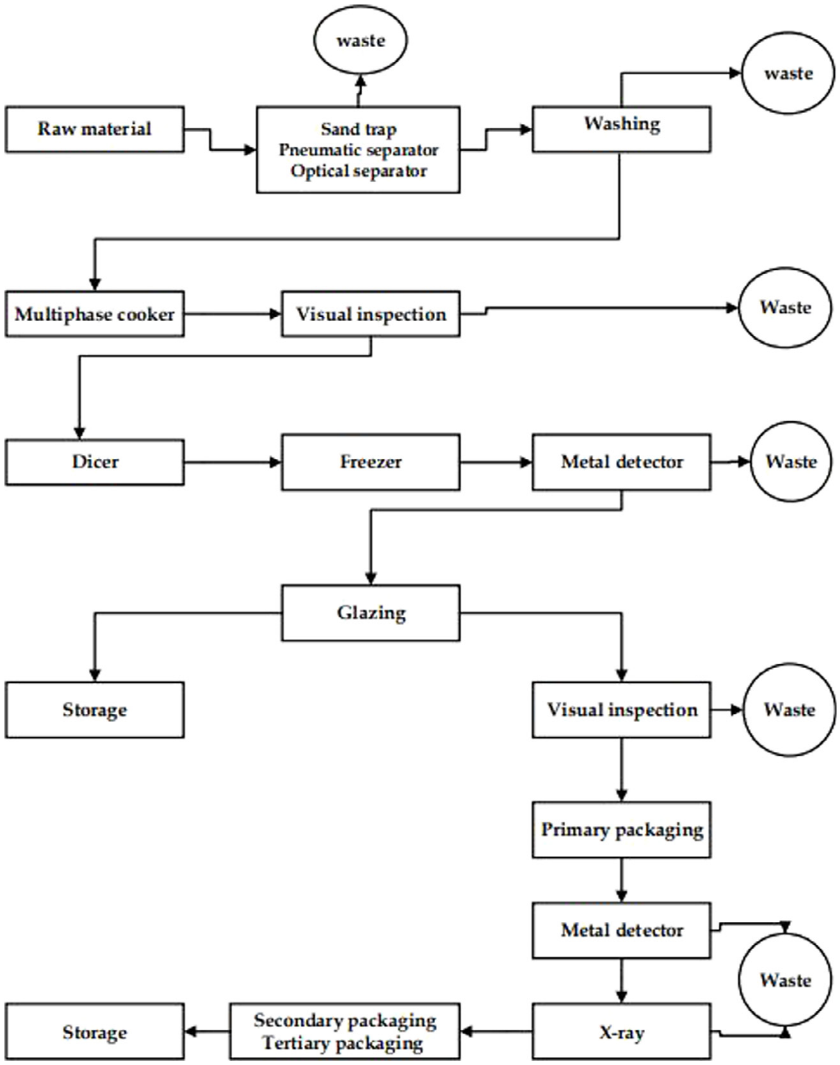

Fig. 2. The schematic flow diagram of the frozen spinach processing phase.

unwanted parts that do not meet quality requirements are conveyed to the biogas plant. The final product is mainly pressed into cubes of different sizes and weights and frozen at −35 °C, with ammonia as the refrigerant in a closed system.

Glazing is often performed on the final product, consisting of wetting the spinach cubes' external surface with water to have a smooth and homogeneous outcome. It is done to improve the aesthetic properties and to prevent losses by friction and breaking. Only some of the products are glazed since some consumers do not appreciate the glazing.

Regarding energy used, electricity from the national grid is used primarily for powering the engines to move the conveyor belts in the processing line, the pneumatic system, the freezer prior to storage, and the compressors to pump the refrigerants for freezing during storage. Additionally, the electricity is used to pump and purify water drawn from the wells, power the electric forklifts, and for lighting offices and laboratories within the plant. However, due to a lack of segregated data on the electricity used and the efficiency of the various operating engines and pumps. The processing facility primarily uses natural gas to heat the multiphase cooker during processing and heating the offices to a lesser extent. We relied on primary data on the company's cumulative electricity and natural gas.

2.3.4. *Packaging and storage*

The packaging steps alternate with various inspections to ensure the removal of defective products. There is a visual inspection, and then the primary packaging is added. After that, the other two quality controls are performed using a metal detector and X-rays. Two main packaging layers protect, store, and transport the products delivered to retail and other businesses. The primary package is plastic, while the secondary container is a carton box. The details on the primary and secondary packaging materials for different frozen spinach products for B-2-C are summarized in Table 2. For B-2-B frozen spinach, the plastic bag used for bulk spinach sent to big vegetable processing companies weighs 1.09 kg for containing about 650 kg of frozen product, with no use of corrugated board boxes. Additionally, plastic bags for packaging 10 kg and 20 kg of frozen spinach sent to food business operators weighs 9 g and 26 g, respectively. The amount of packaging was calculated based on primary data on the type of packaging used and the packaging weight per product.

Standard wooden pallets of dimensions 80 × 120 cm with the capacity to transport between 54 to 81 carton boxes based on the product typology were also considered in the analysis. Using primary data provided by the company about the number of pallets, we calculated the pallet's total weight using an average weight of 23 kg per pallet and chose a proxy EUR-flat pallet from the Ecoinvent database. We assumed pallets would be reused about 3 times throughout their lifecycle. However, foreground information on the distance for transporting the packaging materials was excluded.

The frozen spinach can be stored in freezing cells, placing the cubes into big cardboard boxes lined with plastic bags. The temporal storage duration varies between 2 days to 6 months, and products are distributed upon customers' request. The company sells the bulk frozen spinach to other giant companies for independent packaging while packaging the rest for retail shops and some food business operators. The refrigerant (ammonia) leakage data was calculated based on suggested leakage rates (DEFRA, 2011; Inc. I., 2005) The proposed leakage rates for chillers at the processing plant from the different components/stages were assembly (1%), annual leakage from the operation (8%), and leakage from the dumped refrigeration equipment (5% after considering 95% recovery). We took the operational lifetime of the refrigeration system as 20 years.

2.3.5. *Wastewater treatment*

The plant has a dedicated wastewater treatment system for managing the quality of the wastewater exiting the facility. The treatment system handles all wastewater for all the products, such as spinach, peas, tomatoes, and green beans processed in the plant. However, we could not obtain preliminary information on the water quality since it varies depending on the treatment of the processed products. For instance, blanching for spinach and peas with no chemicals while tomato washing requires chemical cleaning agents. Therefore, we relied on secondary data from the ELCD database (EC, 2022) on wastewater treatment for untreated, slightly organic-contaminated water. We relied on a proxy selection of a closest representative unit process (Wastewater- untreated, slightly organic contaminated EU-27 S).

2.4. *Data quality*

We analyzed primary data from the frozen spinach manufacturer and farmers' direct measurements and official documents, enhancing the reliability and credibility of the study. The data for the frozen spinach production (Table 3) relates to the reference year 2019. The technology used to produce frozen spinach can be best described as an average technology. Background information on the supply of consumed raw materials and energy, such as electricity, natural gas, and packaging materials, was adopted from the Ecoinvent lifecycle database version (v.3.01).

2.5. *Scenarios for spinach residue management*

2.5.1. *Avoided products*

The system under analysis has only one function: producing packaged frozen spinach. However, due to the substantial quantity of spinach residue obtained after processing (30%) and the need for waste valorization, the company transports the residue to a biogas powerplant as feedstock for electricity and digestate production. The biogas digester is primarily fed with maize silage. Thus, we modeled the potential environmental credits associated with generating an equivalent amount of biomethane from spinach residue instead of maize silage. The primary data we used was the calculated maize silage that could be substituted (Table 5), while secondary data on the maize silage production was taken from the Ecoinvent database.

Due to a lack of data on the spinach residue characterization, we performed experiments to determine the dry and volatile matter content at the Biomass Lab of Università Politecnica delle Marche (www.biomasslab.it). We followed the ISO 18134 oven dry method (Standardization IO for. ISO, 2015) to determine the dry matter content. A sample of about 400 g was weighed and set in an oven (105 °C for 24 h) until it reached a constant weight in a ventilated stove ("MPM Instruments" type M 250-VF, Electronic scale). Following the ISO 18123 standard (International Organization for Standardization. ISO, 2015), one gram of the spinach residue was combusted at 900 °C for 7 min in nitrogen using the thermogravimetric analyzer (TGA701 LECO) to determine the volatile matter content. The biochemical methane potential was estimated from the Cropgen database (Cropgen, 2022) based on the results obtained from the analysis. For biomethane conversion to electricity, we assumed the lower heating value of biomethane to be 36 MJ/m^3 and efficiency to be 30% in a cogeneration plant (International Energy Agency , IEA; Florio et al., 2019). However, it should be noted that the biogas production and electricity generating phase was not considered in this study as it was outside the scope of the study.

2.5.2. *Improved processing efficiency*

We also evaluated the combined effect of improved processing efficiency and biogas generation from spinach residue on the various impact categories along the frozen spinach production chain considered. In the first scenario, we considered the reduction of the total residue from 30% to 20% and the remaining residue as a substitute for commercial maize silage (avoided product scenario). The same approach was used in the second scenario, where we quantified the potential gains from reducing the amount of residue through improved processing efficiency from 30% to 10% with the corresponding avoided maize silage production. We compared both cases with the current situation of using the 30% spinach residue as a substitute for commercial maize silage for the biodigester (baseline scenario).

The three scenarios modeled were

Table 2
Description of frozen spinach products (B-2-C) and their corresponding packaging.

Product	Primary package – plastic bag			Net product weight in PP (kg)	Secondary package – carton box		Net product weight in SP (kg)
	Dimension (mm)	*Thickness* (um)	*Weight* (g)		*Dimension* (mm)	*Weight* (g)	
Spinaci cubi bio	650 × 450	75	21	2.50	396 × 260 × 240	331	10
Spinaci cubi bio	560 × 270	62	11	0.75	396 × 260 × 200	321	7.5
Spinaci cubi bio 30 g	560 × 235	60	8	0.45	396 × 260 × 180	312	6.3
Spinaci cubi 50 g	560 × 350	65	14.2	1.00	396 × 260 × 240	331	10
Spinaci cubi	560 × 345	62	13.5	1.00	396 × 260 × 240	331	10
Spinaci cubi	550 × 270	65	9	0.60	396 × 260 × 210	317	8.4
Spinaci a cubetti 50 g	550 × 230	65	8	0.50	396 × 260 × 180	312	7.0
Spinaci a cubetti surgelati	560 × 350	65	11.5	1.00	396 × 260 × 240	331	10
Spinaci fogliolina	540 × 270	–	9	0.45	396 × 260 × 180	312	5.4

Abbreviations: PP = primary package, SP = secondary package.

Table 3
The reference flow of raw materials used to produce frozen spinach at the processing facility. All data shown are with respect to the FU.

Input	Unit	Amount
Cultivated fresh spinach	kg	1.42E+00
Transported spinach	tkm	3.12E−01
Electricity	kWh	5.19E−01
Natural gas	m^3	6.14E−02
Well water	m^3	1.77E−02
Tap water (production and supply)	kg	1.77E+01
Refrigerant (NH_3)	kg	2.10E−05
Packaging		
Plastic (low-density polyethylene)	kg	1.05E−02
Corrugated box	kg	3.85E−02
Printed paper labels	kg	1.73E−04
Pallets (wood)	kg	1.70E−03
Outputs		
Frozen spinach	kg	1.00E+00
Spinach residue	kg	4.18E−01
Emissions		
Refrigerant (NH_3)	kg	3.03E−06
Wastewater treatment	m^3	1.41E+01

1. In scenario 1, we considered that the loss of 30% is sent to the biogas plant and used as a substitute for maize silage. Therefore, the gains will be the avoided production of the equivalent maize silage.
2. In scenario 2, we considered improving processing efficiency will residue content from 30% to 20%, with the remaining residue going to the biogas plant.
3. In scenario 3, we considered improving processing efficiency to reduce residue content from 30% to 10% and the remaining residue going to the biogas plant.

Considering that the losses occur during the processing phase, improving the efficiency during processing in our model does not imply an increase in spinach cultivation or energy use and other inputs like water but rather a corresponding increase in the quantity of packaging materials due to the increase in output. The potential environmental credits benefit the vegetable processing plant, not the biogas, as the study focuses on frozen spinach. Therefore, we did not take into account the impacts associated with the transportation of the residue to the biogas plant.

2.6. Scenarios (Distribution)

Although the analyzed company produces various products, most of the quantity and value produced concerns the bulk formats which are destined for larger and less specialized companies in Italy which package and distribute the finished product. The analysis of the distribution scenarios below is indicative and based on 2020 sales data (regarding the product of the same year and the previous year). To ensure quality and profits, both the company analyzed and the companies that buy the product tend to partly vary suppliers and customers, this generates a variability in the quantities and destinations of the final product which make the scenarios of different years hardly comparable to each other but they can provide the analyzed company with an indication of the environmental advantage/disadvantage of distributing the product in different parts of the continent or the world. The scenario analysis was conducted using 2 different generic product formats (bulk and packaged) mediating between the different specific formats (see Table 3 for example). Furthermore, most of the transport is paid for by the companies that purchase the material, therefore the information available concerns the destination and the product format but not the fate of the material (e.g. packaging for the bulk or subsequent sale of the bulk to a third company, direct use of bulk sold for the HoReCa circuit) this information is useful for defining hypothetical scenarios.

The company distributes its frozen spinach mainly within Italy and exports a small portion to Australia. The frozen spinach is distributed as finished products in their final packaging or as semi-finished products in bulk packaging. Based on the data provided by the company on the amount transported, we modeled the real distribution scenarios for the different products' destinations and examined the corresponding GWP impact (Table 4). However, we excluded refrigerants pallets and for transport due to insufficient primary data. Additionally, we did not include the weight of the wooden pallets used for transporting bulk spinach, which is not required to transport packaged spinach in the final package.

2.7. Life cycle impact assessment

The collected and aggregated data were input into the SimaPro 8.2.3 software with updated databases, including the Eco-invent lifecycle database (v.3.01). This helped construct the process flows to model the production chain. The CML_IA baseline V3.01 impact assessment method (Guinée et al., 2002) was applied to estimate the potential environmental impacts related to the FU. The CML method restricts quantitative modeling to early stages in the cause–effect chain to limit uncertainties. Results can be grouped into several midpoint categories or indicators (Table 6).

3. Results and discussion

In this section, we present the midpoint impact results for the frozen spinach products and their corresponding contribution analysis. We also show the GWP results for the distribution scenarios and compare the potential gains from reducing and valorizing spinach residue as a mitigation strategy.

3.1. Cradle-to-factory gate LCA analysis of frozen spinach

The CML-IA impact scores related to the FU selected for frozen spinach are reported in Table 7. The cultivation phase was a significant contributor, accounting for more than contributed 25% across

Table 4
Transportation means and distances for distributing the frozen spinach from the factory.

Transport step	Distance (km)	Quantity (tons)	Route	Transport means
Regional	0–171	600	by road	Truck (>20t, Euro 4)
National	245–842	2056	by road	Truck (>20t, Euro 4)
Island (Sicily)	1049	480	by road	Truck (>20t, Euro 4)
			by sea	Sea ship
International (Australia)	18436	1.18	by road	Truck (<10t, Euro 4)
			by sea	Freighter oceanic

Table 5
Recycled energy sources and quantification of the avoided products related to the amount of spinach residue generated.

Residue type	Recycled energy source			Avoided products		
	Material	Unit	Amount	Material	Unit	Amount
Spinach residue	Biomethane	m^3	9852.75	Maize silage	ton	220.20
				Electricity	kWh	30327

Table 6
Mid-point impact categories and their description for the CML_IA baseline method.

Impact category	Acronym	Unit	Description
Abiotic Depletion Potential (elements)	ADP (E)	kg Sb eq.	ADP considers the scarcity of non-biological resources such as minerals and fossil fuels globally, hence the limitations in its availability to current and future generations (Hauschild et al., 2013).
Abiotic Depletion Potential (fossil fuel) (van Oers et al., 2002)	ADP (FF)	MJ	
Global Warming Potential 100 yr. Huang et al. (2013)	GWP	kg CO_2 eq.	GWP is an indicator of the potential change in climate attributable to increased concentrations of CO_2, CH_4, and other GHG emissions that trap heat (Čuček et al., 2015; Acero et al., 2017).
Stratospheric Ozone Layer Depletion Potential	ODP	kg CFC-11 eq.	ODP measures the effect of ozone-depleting substances such as CFCs, freons, halogens, and HCFCs on the ozone layer, which causes a more significant fraction of UV-B radiation to reach the earth's surface (Čuček et al., 2015; Acero et al., 2017).
Human Toxicity Potential (Huijbregts et al., 2000)	HTP	kg 1,4-DB eq.	HTP is concerned with the toxic effects of chemical substances on human health. It depends on a compound's inherent toxicity and potential dose. It enables relative comparisons between a more significant number of emitted chemicals with a carcinogenic effect or other adverse human effects for the infinite time horizon (Čuček et al., 2015; Hertwich et al., 2001).
Ecotoxicity		kg 1,4-DB eq.	Ecotoxicity considers emissions of toxic substances such as heavy metals to air, water, and soil. Ecotoxicity potentials are calculated with the USES-LCA, a multi-media fate, exposure, and effects model (Acero et al., 2017; Van Zelm et al., 2009).
Freshwater Aquatic Ecotoxicity Potential	FAETP		
Marine Aquatic Ecotoxicity Potential	MAETP		
Terrestrial Ecotoxicity Potential	TETP		
Photochemical Ozone Creation Potential (Van Zelm et al., 2009; Derwent et al., 1998)	POCP	kg C_2H_4 eq.	POCP forms within the troposphere from various chemicals, including CO, CH_4, SO_2, NOx, NH_4, NMVOC (non-methane volatile organic compounds), and other volatile organic compounds (VOCs) in the presence of heat and sunlight. It is harmful to human health and ecosystems and may potentially damage crops (Čuček et al., 2015; Acero et al., 2017).
Acidification Potential (Huijbregts, 1999)	AP	kg SO_2 eq.	AP deals with the potential of acidifying pollutants such as SO_2, NOx, HCl, NH_3, and HF to form H^+ ions. It can decrease biodiversity and damage ecosystems' quality (Čuček et al., 2015; Acero et al., 2017).
Eutrophication Potential (Huijbregts, 1999)	EP	kg PO_4^{3-} eq.	EP deals with increased aquatic plant growth from an accumulation of nutrients left by over-fertilization of water and soil, such as nitrogen and phosphorus. Nutrient enrichment may cause fish death, declining water quality, decreased biodiversity, and foul odours and tastes (Čuček et al., 2015)

all impact categories. TETP, ADP (E), EP, and AP contributed a percentage share of 93.61%, 92.73%, 85.16%, and 69.30%. The average GWP for spinach cultivation was 4.82E−01 kg CO_2eq., with significant contributions coming from direct N_2O gas emitted into the air from inorganic nitrogen-based fertilizers (48.49%) and indirect emissions from the synthesis and use of fertilizers (26.57%. The spinach was predominantly cultivated under the integrated farming system (about 93%). There was a significant variation between the integrated spinach and organic spinach across all the impact categories, with the integrated spinach being far more impacting. Evidently, most of the impacts were associated with agrochemicals like fertilizer and pesticides and, to some degree, mechanized farm activities like tillage and irrigation.

Regarding the other phases, different materials and processes had varying degrees of impact on the various midpoint impact categories. Packaging materials, especially corrugated boxes and pallets, and energy from electricity and natural gas were the main contributors across several impact categories (excluding the cultivation phase). Transportation of spinach from the farm gate to the factory gate contributed less than 10% to the overall impact across all selected midpoint categories, as shown in Fig. 3. Considering that the cultivation phase has been extensively covered in a previous paper (Pedretti et al., 2021), the relative comparison of the processing phases (spinach supply, processing, packaging, and wastewater treatment) are only shown in Fig. 3. For this reason, the subsequent results section of this paper focuses solely on the postharvest phases of the spinach production chain (fresh spinach supply, processing, packaging, and wastewater treatment).

3.1.1. Depletion of abiotic resources (ADP)

The abiotic depletion potential for elements (E) and fossil fuels (FF) for the frozen spinach was 3.48E−07 kg Sb eq. and 3.73 MJ, respectively. The main contributors for ADP (E) were primarily related to the packaging materials (83.70%), particularly corrugated board boxes (67.40%) and pallets (15.51%). Generally, more impacts are

Table 7
Environmental impact scores for frozen spinach production with respect to the FU.

Impact category	Unit	Total	Cultivation	Spinach supply	Processing	Packaging	Wastewater treatment
ADP (E)	kg Sb eq.	4.79E−06	4.45E−06	2.43E−09	4.78E−08	2.92E−07	6.59E−09
ADP (FF)	MJ	6.95E+00	3.23E+00	0.00E+00	2.71E+00	1.02E+00	0.00E+00
GWP	kg CO_2 eq.	1.55E+00	4.82E−01	6.03E−02	3.98E−01	9.26E−02	5.16E−01
ODP	kg CFC-11 eq.	8.29E−08	2.85E−08	1.23E−10	4.65E−08	4.74E−09	3.09E−09
HTP	kg 1,4-DB eq.	1.67E−01	7.77E−02	4.55E−03	2.60E−02	3.85E−02	2.05E−02
FAETP	kg 1,4-DB eq.	8.18E−02	4.73E−02	1.59E−04	1.06E−02	2.12E−02	2.52E−03
MAETP	kg 1,4-DB eq.	4.04E+02	1.44E+02	8.26E−01	1.56E+02	9.79E+01	5.43E+00
TETP	kg 1,4-DB eq.	2.50E−03	2.34E−03	4.25E−06	4.79E−05	8.76E−05	2.00E−05
POCP	kg C_2H_4 eq.	3.12E−04	7.68E−05	1.95E−05	1.23E−04	3.24E−05	6.01E−05
AP	kg SO_2 eq.	1.35E−02	9.37E−03	4.13E−04	2.18E−03	4.46E−04	1.11E−03
EP	kg PO_4^{3-}eq.	7.49E−03	6.38E−03	9.98E−05	1.50E−04	1.59E−04	7.03E−04

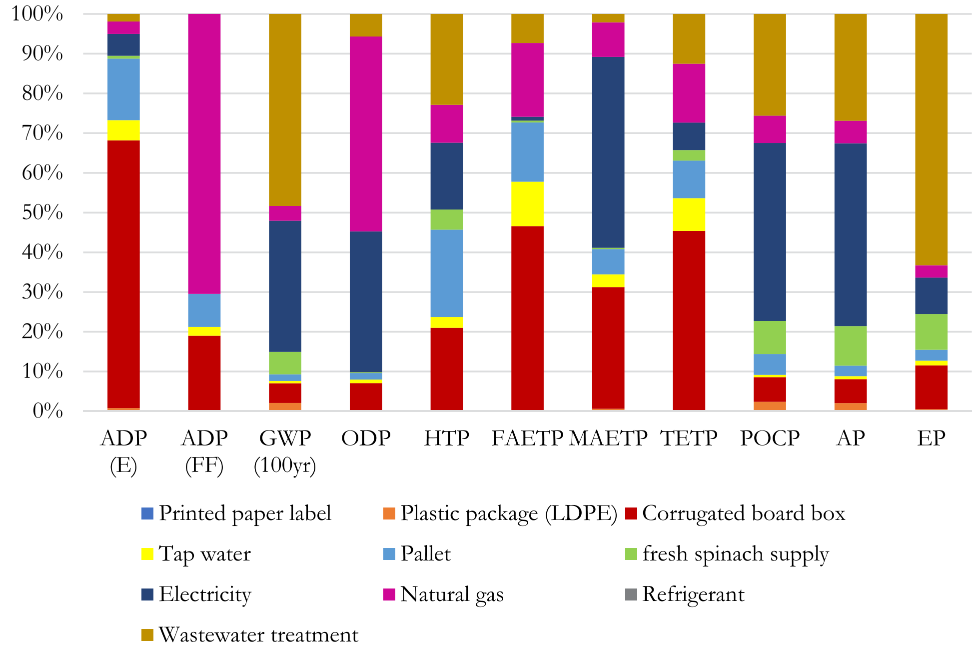

Fig. 3. The relative contribution analysis for frozen spinach production relating to the fresh spinach supply, processing, packaging phases, and wastewater treatment.

related to packaging materials (corrugated board boxes) when products are in smaller portions (i.e., frozen spinach for retail shops and food business operators). In contrast, fewer packaging materials are required when products are transported in bulk. The company does not use corrugated board boxes for bulk packaging, storage, and distribution. The supply of fresh spinach from the various farm gates to the factory and refrigerant contributed about 1%.

Regarding the impact score of ADP (FF), natural gas (70.46%) and corrugated board box (18.88%) were the most impacting inputs for ADP (FF) (Fig. 3). ADP (FF) considers the scarcity of fossil fuels globally. Hence it considers the potential limitations in the availability of natural gas due to its extraction and use. The processing facility primarily uses natural gas to heat the multiphase cooker during processing and heating the offices to a lesser extent. Pallets also contributed (8.34%) to the overall impact, while the other inputs combined for less than 3%.

3.1.2. Global warming potential (GWP)

The global warming potential (GWP 100 yr.) was 1.07 kg CO_2eq./kg frozen spinach (including wastewater treatment). While excluding the wastewater treatment, it was 0.55 kg CO_2eq./kg frozen spinach (Table 7). The main contributors were wastewater treatment (48.35%) and electricity (33.03%), as shown in Fig. 3. Regarding wastewater treatment, spinach processing generally generates less polluted wastewater. Therefore, the potential impacts associated with the wastewater treatment could be overestimated, considering we relied on a proxy selection of a fairly representative unit process (Wastewater-untreated, slightly organic contaminated EU-27 S) to model the inventory in the SimaPro software due to the unavailability of enough domain knowledge to create a new one. Given that we relied on aggregated data for electricity used and the lack of sufficient information on the efficiency of the various operating engines and pumps, the impacts associated with electricity could be reduced if we consider segregated energy directly related to the frozen spinach processing. Fresh spinach supply from the farm to the factory also contributed (5.65%) to the overall GWP score. About 50% of the fresh spinach is sourced from the Marche region, where the processing facility implies a shorter distance for transporting the product and could explain the relatively low impacts associated with this phase. While for longer distances, trucks with a greater loading capacity (23 tons) are used for the supply. Additionally, no losses are reported during transportation, given that the loading factor is 50%, ensuring the fresh spinach's integrity and quality.

3.1.3. Ozone layer depletion (OD)

The stratospheric ozone layer depletion potential (ODP) for 1 kg frozen spinach was 5.44E−08 kg CFC-11 eq. (Table 7). In terms of principal contributing inputs, natural gas (49.02%) and electricity (35.47%) were the major contributors. Corrugated board boxes and wastewater treatment also contributed 7.05% and 5.69%, respectively. Results could be attributed to the several ozone-depleting substances, such as methane, ethane, bromochlorodifluorocarbons, bromotrifluoro, and other CFCs, halogens, and HCFCs associated with background processes for natural gas and electricity production.

3.1.4. Human toxicity (HT)

The human toxicity potential (HTP) was 8.95E−02 kg 1,4-DB eq. per 1 kg frozen spinach (Table 7). The contribution analysis (Fig. 3) shows a similar contribution from wastewater treatment (22.87%), pallets (22.01%), corrugated board boxes (20.72%, and electricity (16.80%). HTP considers the potential effects of toxic chemical substances, particularly carcinogenic effects, on human health. Many such compounds, such as selenium, chromium VI, hydrogen fluoride, thallium, and benzene, are associated with the upstream processes of producing packaging materials and electricity. While in the case of wastewater treatment, they are considered to as emitted chemicals, mainly inorganic, in the polluted water.

3.1.5. Ecotoxicity (FAET, MAET, TET)

The freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), and terrestrial ecotoxicity potential (TETP) scores for 1 kg of frozen spinach were 3.45E−02 kg 1,4-DB eq., 2.60E+02 kg 1,4-DB eq., 1.60E−04 kg 1,4-DB eq., respectively. The contribution analysis per 1 kg of frozen spinach in Fig. 3 shows that corrugated board box was a major contributor to FAETP, MAETP, and TETP with shares of 46.33%, 30.66%, and 45.16%, respectively. Other significant contributors to FAETP were natural gas (18.56%), pallets (14.92%), and tap water production and supply (11.18%). While for MAETP, electricity (48.06%), natural gas (8.71%), and pallets (6.36%) followed in that order. Regarding the contribution analysis for TETP, the other relevant contributors were natural gas (14.80%), wastewater treatment (12.53%), pallets (9.45%), tap water production and supply (8.25%), and electricity (6.93%). Ecotoxicity considers emissions of toxic substances such as heavy metals such as nickel, vanadium, copper, and cobalt to air, water, and soil, which in this case were mostly related to the upstream processes related to the production of the inputs.

3.1.6. Photochemical ozone creation (POC)

The photochemical ozone creation potential (POCP) was 2.35E−04 kg C_2H_4 eq. with respect to 1 kg frozen spinach ready for distribution (Table 7). Electricity (44.81%) and wastewater treatment (25.60%) were the main contributors. Other minor contributions came from the transportation of fresh spinach (8.30%), natural gas (6.89%), and corrugated board boxes (6.20%). The main identified chemical compounds with the potential to cause photochemical smog were sulfur dioxide, carbon monoxide, and methane, which were related to the background processes of electricity production and wastewater treatment.

3.1.7. Acidification (AP)

The results in Table 7 shows that the acidification potential (AP) was 4.15E−03 kg SO_2 eq. for 1 kg of frozen spinach. Again, the main contributors were electricity (46.03%) and wastewater treatment (26.86%). Other minor contributions came from the transportation of fresh spinach (9.94%), corrugated board box (6.03%), and natural gas (5.69%), as shown in Fig. 3. Sulfur dioxide, nitrogen oxides, and ammonia were the primary acidifying pollutants identified.

3.1.8. Eutrophication (EP)

The eutrophication potential (EP) was 1.11E−03 kg PO_4^{3-} eq. with respect to 1 kg frozen spinach ready for distribution (Table 7). From the contribution analysis (Fig. 3), wastewater treatment was by far the primary contributor, accounting for 63.26% of the total score. Other significant contributors were corrugated board boxes (11.01%), electricity (9.20%), and fresh spinach transportation (8.97%). Considering that EP deals with increased aquatic plant growth from an accumulation of nutrients left by over-fertilization of water and soil, the main compounds identified were nitrogen, nitrogen dioxide, nitrate, and phosphate, which were mainly related to the treatment of sightly organic wastewater and the upstream processes of corrugated board box.

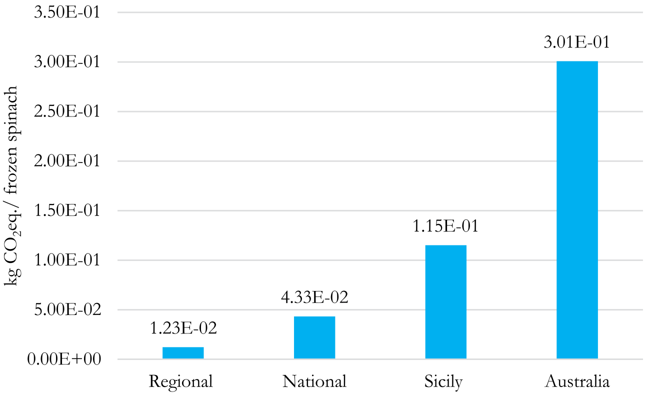

Fig. 4. The GWP for the frozen spinach distribution scenarios (processing plant to the retail company).

3.2. GWP for frozen spinach distribution scenarios

The GWP results for the categorized distribution scenarios based on distance are shown in Fig. 4. The results ranged between 1.23E−02 to 3.01E−01 kg CO_2 per kg frozen spinach, with regional recording the least score and international distribution (Australia) having the highest. Bulk frozen spinach in big plastic bags, weighing an average of 680 kg, is transported to giant vegetable processing companies for final packaging and further distribution. In comparison, packed frozen spinach relates to products sent directly to warehouses of retail shops and food business operators as ingredients in their food preparation. On the regional distribution level, bulk frozen spinach recorded a relatively lower score than packed frozen spinach primarily because most of the bulk spinach at transported at total capacity over shorter distances, as shown in the contribution analysis in Fig. 5. However, on the national level, a slightly higher score was obtained for bulk frozen spinach than packed frozen spinach owing to the farther destination points and the different load factors (<100) depending on the quantity transported. It is also worth noting that if the excluded additional input (wooden pallet) for transport is considered, the impacts associated with bulk spinach will be greater.

Similarly, higher GWP scores were obtained for the distribution of packaged frozen spinach to Sicily (island) and Australia (international). Evidently, this was due to the longer distances and the smaller quantity of products transported. Additionally, different transport means and load capacities were involved. Most of the burdens were associated with the cargo ship for packed spinach sent to Australia. For the island scenario, impacts mainly were related to the transport truck due to the long road distances from the company to the port and from the port to the destination. It is worth noting that the giant retailers and food business operators are responsible for the bulk spinach transportation to their premises, primarily by refrigerated trucks with a payload of 20t loaded at total capacity. However, due to the unavailability of primary information on the trucks used, we did not include refrigerants as input for this phase.

The results obtained for this phase relate to the company's real distribution scenarios for 2019–2020. As such, they can significantly change depending on the market demands, particularly the amount of product requested by the customers and the location of customers, including potentially new customers. Thus, the results are peculiar to this company and should not be generalized as a typical distribution phase for frozen spinach in Italy. Additionally, we did not consider any losses at this phase which can significantly alter the results if substantial losses occur.

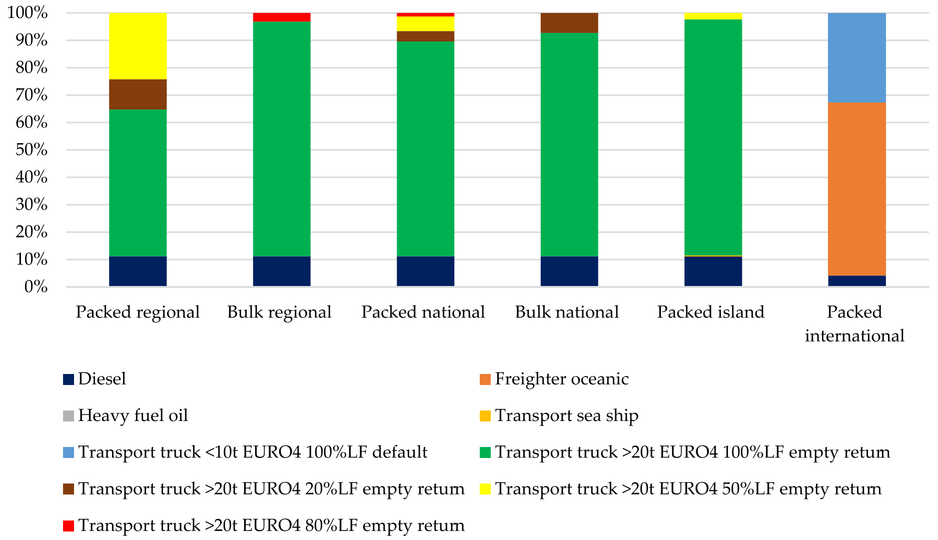

Fig. 5. The relative process contribution to the GWP for the distribution scenarios considered.

3.3. *Supply chain contribution analysis*

In addition to the environmental impact categories explained in Section 3.1, the impacts related to the various phases were further investigated. As earlier stated, the transportation of fresh spinach from the farm gate to the factory gate contributed less than 10% across all impact categories. Most notable contributions were made to AP (9.94%), EP (8.97%), POCP (8.30%), and GWP (5.65%). The impacts are primarily related to the combustion of fuel to transport the product. Again, it is worth noting that the sourcing of fresh spinach is peculiar to the processing plant and should not be generalized as a representation of the Italian frozen spinach supply chain. However, most food processing companies typically source their raw materials from many locations. Thus, the results could significantly change based on the quantity transported, the distance traveled, the type of transport means employed, and the load capacity.

In the processing phase, a larger contribution came from electricity, natural gas, and wastewater treatment. Electricity was most predominant in MAETP (48.06%), AP (46.03%), POCP (44.81%), ODP (35.47%), and GWP (33.03%). In comparison, natural gas was the main contributor to ADP FF (70.46%) and ODP (49.02%). Wastewater treatment was also a significant contributor to EP (63.26%), GWP (48.35%), and AP (26.86%). Refrigerant (ammonia) contributed less than 1% across all the impact categories, mainly because several other vegetable products are stored together with the spinach. Thus, a small percentage (17%) was attributed directly to frozen spinach based on a mass allocation.

Regarding the packaging materials, the corrugated board box was most impacting, followed by pallets, with the least being the low-density polyethylene bags. The secondary package (corrugated board box) mainly impacted ADP E (67.40%), FAETP (46.33%), and TETP (45.16%). The pallets also significantly impacted HTP (22.01%), ADP E (15.51%), and FAETP (14.92%). The pallet is not necessarily a packaging material and only aids in transporting the packaged material. Additionally, it can be reused many times before its end-of-life, as such impacts related to the pallets can be reduced if existing ones are managed well to prevent damages to extend their use beyond their estimated lifespan. The low-density polyethylene bags and the printed paper labels contributed less than 3% to the total scores across the impact categories assessed. Generally, plastic packages are less environmentally impacting due to their lightweight and less amount used.

Additionally, the impacts of plastic pollution on ecosystems and human health from single-use plastic formats still need to be adequately characterized. Thus, like most packaged foods, frozen spinach should be managed appropriately after its use to reduce negative environmental impacts. In this study, we did not consider the end-of-life treatment of the packaging materials, which includes recycling, combustion, and landfill. Considering that more than 90% of the corrugated board box and pallets can be recycled, substantial environmental gains can be obtained, reducing the overall environmental impacts associated with frozen spinach.

3.4. *Sensitivity analysis for alternative spinach residue management*

The results for potential environmental gains in relation to the post-cultivation phases for the different scenarios considered are shown in Fig. 6. Due to the circular economy concept proposed in the European Green Deal, there has been an advocacy for valorizing agricultural residues because of the perceived environmental benefits. The results showed that reducing the spinach residue from 30% to 10% (scenario 3) with the remaining residue as maize silage substitute was the most environmentally beneficial to the frozen spinach producer, while the 30% spinach residue sent to the biogas plant and used as a substitute for maize silage was the least beneficial (scenario 1). In all midpoint categories, reducing spinach residue from 30% to 20% (scenario 2) reduced the environmental impacts between the range of 12 to 20%, while reducing spinach residue from 30% to 10% reduced the environmental impacts between the range of 21 to 26%. In contrast, except for TETP (13%), scenario 3 resulted in less than 7% gains for all the impact categories for the postharvest phases. The yields for scenario 3 were lower because spinach residue has a relatively low energy content and total volatile solids and would require considerable quantities to displace enough commercial maize silage for appreciable gains. Therefore, it can be implied that using multiple waste management strategies, including improving processing efficiency, would yield more direct ecological benefits to the vegetable processor. It should also be considered that using spinach residue as a feedstock for biogas generation would require the transport of the residue and energy and materials for converting the organic material into biogas and, subsequently, electricity. Feedstock transport over long distances could be environmentally impacting, so local sourcing should be prioritized. Reducing the amount of residue could also increase the amount of maize silage for the biogas plant or the sourcing of organic residue from other places, potentially resulting in higher environmental impacts. Thus, a more holistic assessment of this phase would ensure a better comparison with gains from residue reduction.

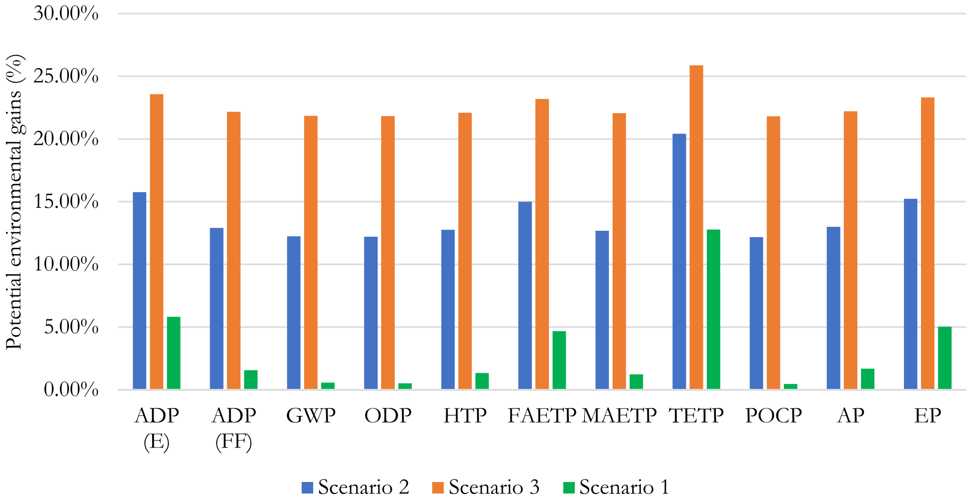

Fig. 6. The potential environmental credits to the post-cultivation phases (farm gate-to-factory gate) from the different scenarios of spinach residue management considered.

3.5. Discussion

Horticultural production can be environmentally impacting, given the intensive use of resources, such as land, water, agrochemicals, and labor (Wainwright et al., 2014). Therefore, most existing environmental impact assessment studies on spinach focus on the cultivation phase. The results vary considerably depending on several factors, including the cultivation system, other phases included in the system boundary, such as transportation, cooling, and packaging, and the data quality and uncertainty (Theurl et al., 2017; Seo et al., 2017; Stoessel et al., 2012; Shiina et al., 2011; Audsley et al., 2009). However, Frankowska et al. (2019) assessed the environmental impacts of vegetables consumed in the UK on a life cycle basis. They compared the impacts on local production and imported vegetable products. To the best of our knowledge, this is the only study that has investigated frozen spinach's environmental impacts. The results for the midpoint impact categories did not vary considerably by geographical region when comparing spinach products produced in the UK and imported spinach products. However, imported spinach was slightly higher, evidently due to transportation impacts. For instance, they reported GWP results of 0.59 kg CO_2eq. and 0.71 for 1 kg frozen spinach produced in the UK and imported spinach, respectively (excluding the retail and use phases). The processing phase was the most impacting phase for GWP in both cases, followed by the cultivation phase. However, they reported packaging as the most impacting phase for canned spinach, which stresses the importance of selecting excellent packaging, considering that more than 60% of the spinach was sold in cans in the UK. It is worth noting that the results are primarily based on secondary data and various assumptions due to the unavailability of primary data leading to high data uncertainty.

We also compared our results to another LCA study on frozen vegetables in Italy. Ilari et al. (2019) assessed the impact of frozen green bean production and processing in Central Italy. Generally, the results for the various impacts were slightly lower than those reported in this study except for ADP (FF), HTP, and MAETP. They found the global warming potential for producing 1 kg frozen green beans as 0.74 kg CO_2 eq. The results are comparatively lower than our study, primarily due to the exclusion of wastewater treatment and the packaging of bulk products in plastic bags with no use of corrugated board boxes.

4. Conclusion

This study assessed the life cycle environmental impacts of packaged frozen spinach at the factory gate of a food processor in Italy. The assessment encompasses the cultivation, fresh spinach transport to the processing facility, processing, packaging, storage, and wastewater treatment. The distribution scenarios of the packaged frozen spinach from the factory gate to the different destinations were also investigated, while post-retail activities were excluded due to the unavailability of sufficient information.

Focusing on postharvest activities, the supply of fresh spinach from the farm to the factory accounted for less than 10% of the total impacts assessed. A contribution of about 9% was obtained for AP, EP, and POCP, mainly due to direct emissions of polluting compounds from diesel combustion. About 50% of the fresh spinach was sourced from the region (within 120 km) where the processing plant was located, resulting in relatively lower impacts. Thus, increasing the share of local spinach production in the Marche region with an efficient logistics system could further reduce the environmental impacts of frozen spinach. The processing phase of the spinach was significantly impactful for different impact categories. The most notable inputs and processes were electricity, natural gas, and wastewater treatment. The primary data for electricity consisted of the cumulative electrical energy use in the plant, which included other uses not directly related to spinach processing. Segregating this data could potentially lead to a reduction in impacts. Furthermore, the technology employed in the plant can be best described as average, which implies a lower efficiency of engines for moving conveyor belts. Regular maintenance and upgrading of these engines could result in environmental gains. Complementing electricity from the national grid with renewable energy, such as photovoltaic cells, can also be environmentally beneficial. Packaging, particularly corrugated board boxes and pallets, was also significantly impacting for multiple impact categories assessed. Plastic bags (low-density polyethylene) and printed paper labels were the least impactful, accounting for less than 3% of the total shares for all impact categories. Adopting good end-of-life treatment of the packaging materials, such as reusing and recycling the pallet and corrugated board boxes, can considerably result in environmental gains for the frozen spinach.

Including the cultivation phase substantially increased the impact scores for all impact categories. The global warming potential increased from 1.07 kg CO_2 eq. to 1.55 kg CO_2 eq. for 1 kg frozen spinach, while percentage shares of TETP, ADP (E), EP, and AP rose by 93.61%, 92.73%, 85.16%, and 69.30%, respectively. The type of cultivation system employed significantly affected the impact scores. The integrated spinach was generally more environmentally impacting than the organic spinach across most midpoint categories, primarily due to the use of fertilizers and higher amounts of pesticides. For instance, the global warming potential indicator for producing 1 kg of fresh spinach was 0.20 kg CO_2 eq. and 0.075 kg CO_2 eq. for frozen integrated spinach and frozen organic spinach, respectively.

The global warming potential scores for the retail distribution scenarios show regional distribution to be less impacting (1.23E−02 kg

CO_2 eq.) than the national (4.33E−02 kg CO_2 eq.), island (1.15E−01 kg CO_2 eq.), and international (3.01E−01 kg CO_2 eq.). Differences were due to the amount of product transported, distance traveled, and the transport means employed. Although product distribution is heavily linked with economic benefits, environmental considerations should be made to ensure that more efficient logistic systems are in place.

As shown by the sensitivity analysis to compare the potential environmental credits for the processing phase for different spinach residue management strategies (i.e., reducing the amount of residue to 10% and 20% and substituting maize silage production with the 30% spinach residue as feedstock for biogas production), spinach waste reduction was more environmentally beneficial to the horticultural processor. When spinach residue is reduced to 20% and 10%, total impacts for all impact categories also decrease by 12% and 22%, respectively. The benefit of using the current amount of spinach residue to produce biomethane was less than 7% across all impact categories except terrestrial ecotoxicity (13%). Therefore, reducing spinach waste along the processing line would provide direct economic and environmental benefits to the food processor. There is also the need to investigate alternative ways to valorize spinach residues, such as biotreatment with insects (that produce alternative products with high economic value), which may have higher ecological gains.

Further studies could be done to include the retail, use, and waste disposal phases. Since spinach is also a food ingredient, a nutritional life cycle assessment could also be carried out to assess the environmental and nutritional impacts of consuming spinach. Such findings could interest consumers, helping them make informed choices towards sustainable consumption of frozen spinach.

CRediT authorship contribution statement

Ester Foppa Pedretti: Conceptualization, Resources, Writing – review & editing, Supervision. **Daniele Duca:** Conceptualization, Investigation, Writing – review & editing, Supervision. **Martina Ballarini:** Methodology, Formal analysis. **Kofi Armah Boakye-Yiadom:** Methodology, Investigation, Writing – original draft, Writing – review & editing. **Alessio Ilari:** Methodology, Formal analysis, Investigation, Writing – original draft.

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.

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