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Life cycle assessment of open field sea fennel production in central Italy

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ABSTRACT

Sea fennel is a minor crop of emerging socioeconomic importance in the Mediterranean region. Despite its potential, there has been no assessment of its environmental impacts to support its perceived sustainability for broader promotion. Using a life cycle assessment (LCA), we evaluated the environmental performance of sea fennel production in an open field. A cradle-to-farm gate assessment was conducted using a functional unit (FU) of 1 kg of fresh sea fennel at the farm gate. The system boundaries encompassed the nursery, cultivation, and waste management phases. Primary data was collected from farms in the Marche region of Italy. The environmental impacts were assessed using the Environmental Footprint (EF) 3.0 midpoint life cycle impact assessment method. From the results, the primary hotspot input was plastic mulch, with a relative contribution of over 50% across most impact categories. Increasing the recycling rate from 30% to 70% substantially improved the environmental performance of sea fennels, reiterating the need for further investment in plastic recycling. This study provides insights into the environmental sustainability of sea fennel production. Findings demonstrate that sea fennel cultivation offers a promising path toward sustainable biomass production, underscoring the prospects for its commercial exploitation.

1. Introduction

Sea fennel (*Crithmum maritimum* L.) is a perennial edible halophyte found predominantly around the coastal areas of the Mediterranean. Although considered an underutilized crop, it is experiencing a resurgence in interest due to its potential applications in various fields, such as food, health, pharmaceutical, fuel, phytoremediation, desalination, and packaging (Kraouia et al., 2023; Gómez et al., 2023; Maoloni et al., 2021, 2023a; Piatti et al., 2023; Karkanis et al., 2022; Renna, 2018). This renewed interest in sea fennel coincides with growing concerns about climate change and its impact on food security, positioning it as a valuable crop due to its inherent resilience to harsh environmental conditions (Renna, 2018; Montesano et al., 2018). Moreover, it is perceived to have minimal environmental impacts due to its low resource requirement for growth (Zenobi et al., 2021). However, despite these perceived benefits, a knowledge gap exists on the environmental impacts of its production. This lack of data hinders informed decision-making regarding its potential for sustainable agriculture.

Sea fennel has recently been highlighted as a cash crop because of its potential economic importance. It is a rich source of many health-promoting compounds such as polyphenols, carotenoids, minerals, vitamins, ω-3 and ω-6 essential fatty acids, essential oils, and dietary fiber (Meot-Duros and Magné, 2009; Souid et al., 2021; Jallali et al., 2014; Veršić Bratinčević et al., 2023; Politeo et al., 2023; Nartea et al., 2023). Due to the high abundance of phenolic compounds, mainly hydroxycinnamic acids and flavonoids, it has a high antioxidant capacity (Maoloni et al., 2023a; Veršić Bratinčević et al., 2023; Nartea et al., 2023). Sea fennel extracts also have various nutraceutical properties, including antiproliferative, antimicrobial, anti-inflammatory, and anticarcinogenic functional activities (Karkanis et al., 2022; Nabet et al., 2017; Giordano et al., 2021; Pedreiro et al., 2023; Meot-Duros et al., 2010). As a result, it is being harnessed to produce innovative foods as well as an ingredient in other food products to enhance their taste and functionality (Maoloni et al., 2021; Maoloni et al., 2021; Renna, 2018; Maoloni et al., 2022; Radman et al., 2023; Maoloni et al., 2023b). Sea fennel's market holds significant growth potential due to its health-promoting compounds and the rising consumer trend towards such beneficial foods. However, this potential is challenged by the unsustainable practice of indiscriminate wild harvesting. This has led to the disappearance of sea fennel in some European habitats, prompting legal protections and bans on wild harvesting (Kraouia et al., 2023). Therefore, cultivation is crucial for meeting future market demand.

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While the socioeconomic benefits of sea fennel are promising, a comprehensive understanding of its environmental impact is equally vital. This versatile plant is an important ecosystem component and offers a potential solution for several environmental challenges, such as climate change, freshwater scarcity, and arable dryland desertification. In addition to sequestering carbon (Panta et al., 2014; Atia et al., 2009; Lal, 2019), providing habitat, and supporting biodiversity (Radulovich et al., 2020), it can also thrive on marginal lands with high salinity and arid conditions. However, sea fennel cultivation faces challenges like irrigation with saline water and the need for optimized production and processing technologies (Radulovich et al., 2020). Despite these challenges, its inherent resilience and minimal input requirements make it a potentially sustainable crop. Establishing a baseline understanding of its environmental performance is important to ensure its long-term viability, which can inform strategies to maximize yield while minimizing environmental impacts.

Life cycle assessment (LCA) is a widely recognized framework for evaluating the environmental performance of a product or service by estimating direct and indirect impacts across the entire supply chain (Rebitzer et al., 2004). LCA adheres to ISO 14040 and 14044 standards (ISO, 2006a; ISO, 2006b) and is extensively employed to assess the cultivation of various agricultural products across different production systems, facilitating informed decision-making at multiple levels (Alhashim et al., 2021). With consumers displaying an increasing concern for the environmental aspects of the products they choose, especially organic products, LCA studies are gaining momentum (Nel et al., 2011; Boakye-Yiadom et al., 2023; Karlsson Potter and Röös, 2021). Moreover, the growing importance of green procurement and environmental marketing has incentivized food processors and businesses to seek information on the impact assessment of their products, which they can communicate to consumers (Cooper and Fava, 2006; Foppa Pedretti et al., 2021; Pedretti et al., 2023). Despite the growing adoption of LCA in agricultural research, no study has assessed the environmental impacts of cultivating sea fennel. This lack of data hinders our ability to support its perceived sustainability. Relying solely on perceived benefits may be misleading, as biases and misunderstanding trade-offs can hinder decision-making. Therefore, a comprehensive LCA of sea fennel production is necessary to establish a data-driven understanding of its environmental sustainability.

To address this knowledge gap, we assess the environmental impacts of open-field sea fennel cultivation in central Italy using LCA. The modeled system covers the nursery and cultivation phases, providing a comprehensive inventory of environmental flows currently absent in scientific literature. We analyze the environmental impact across various impact categories. Furthermore, the study employs hot spot and sensitivity analyses to identify significant processes and factors influencing its environmental performance. Additionally, the study goes beyond traditional LCA methods by integrating the nutritional aspects into the environmental impact assessment. We apply micronutrient-based functional units to evaluate the environmental performance for a more comprehensive evaluation. The findings of this study offer valuable insights to guide the development of sustainable practices for sea fennel cultivation, ultimately contributing to addressing global challenges like climate change and food insecurity.

2. Material and methods

We calculated the environmental performance of the product following the ISO 14040/14044 standards (ISO, 2006a; ISO, 2006b) and specific product rules published within the framework of the International Environmental Product Declaration (EPD) System for arable and vegetable crops (European Commission and Joint Research Centre, 2010). We conducted this study using the LCA SimaPro software version 9.4. Background data for ancillary materials and energy were obtained from the Ecoinvent database version 3.9 – allocation (cut-off by classification) (Wernet et al., 2016).

2.1. Goal and scope definition

The study aims to evaluate the environmental performance of sea fennel cultivated under an open field system in central Italy. The primary purpose of the product system is to grow commercial quantities of sea fennel for further processing as a condiment. The functional unit used is 1 kg of freshly harvested sea fennel at the farm gate from an open field production in Italy between 2019 and 2025. Additionally, we set up another functional unit of 1 sea fennel seedling per one cycle of greenhouse at the nursery gate. The primary data is obtained from a producer of sea fennel-based food preserves (Rinci S.r.l., Castelfidardo, Ancona, Italy) in the Marche region of Italy. The production is carried out on a 2.5 ha field in the Conero Natural Park, south of Ancona.

The system boundaries include the nursery, cultivation, transportation of materials, and waste management. The system boundary includes foreground and background processes. The foreground inventory data were obtained directly from the producer. The nursery phase encompasses all resources related to material inputs required to produce sea fennel seedlings (Fig. 1A). The cultivation phase covers farm inputs, farm operations, and end-of-life of mulching material (Fig. 1B). We performed an attributional LCA analysis on the main system (i.e., “cradle-to-farm gate,” which considers all the interventions involved in producing 1 kg of sea fennel, excluding potential system changes. Thus, average data are used for the background processes. Allocation of input and output flows of processes for the product system was carried out on a mass basis, where necessary. Additional functionalities, such as recycled material and energy produced from waste management, are accounted for through a system expansion.

2.2. Life cycle impact assessment

We evaluated the impacts of the sea fennel, per the selected functional units, in terms of climate change (CC) estimated over a 100-year horizon, ozone depletion (OD), ionizing radiation (IR), photochemical ozone formation (POF), particulate matter (PM), human toxicity, non-carcinogenic (HTNC), human toxicity, cancer (HTC), acidification (A), eutrophication freshwater (EF), eutrophication marine (EM), eutrophication terrestrial (ET), ecotoxicity freshwater (ETF), land use (LU), water use (WU), resource use, fossils (RUF), and resource use, minerals and metals (RUM) using the Environmental Footprint (EF) 3.0 midpoint life cycle impact assessment (LCIA) method (Fazio et al., 2018).

2.3. Process modeling (life cycle inventory)

This section covers the description and modeling of the two main phases considered in the study. The foreground inventory data was obtained through field visits, interviews, and questionnaires administered to the producer. The data is structured into the nursery and the main cultivation phase.

2.3.1. Nursery phase

Sea fennel seedlings are raised in a greenhouse structure on an area of 60 m^2 near the cultivation field. The structure consists of 8 metal arches of 2.5 m and a height of about 3 m. The structure is covered with a low-density polyethylene (LDPE) film and a thickness of 0.15 mm. The seeds obtained from the sea fennel field are sown in plastic trays containing blonde peat of density 120 kg/m^3 above a top layer of vermiculite (3 mm). The watering ratio is every day, two times a day for 8 min each. The seeds germinate after 21–30 days of planting and mature in 5–6 weeks, with a 70–80% germinability. The viable seedlings are then transplanted on the field. Table 1 shows the inventory table for producing sea fennel seedlings. We considered the life span of the plastic tray to be five years and the polyvinyl chloride irrigation pipes to be seven years. For the infrastructure, the metal arches were assumed to have a lifespan of 20 years, while the LDPE cover was considered to have a lifespan of three years (see Table 1).

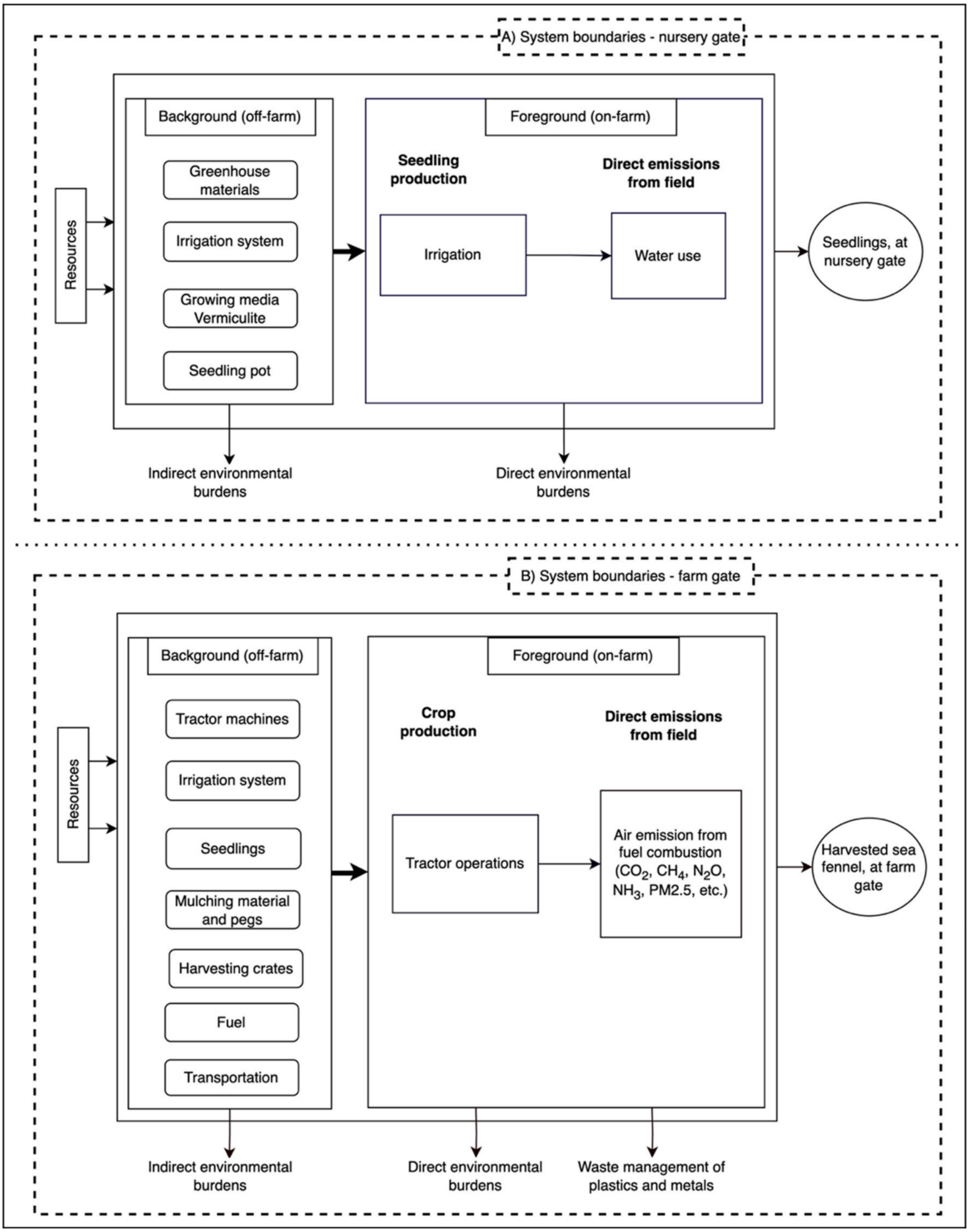

Fig. 1. A represents the system boundary for the cradle-to-nursery gate LCA of sea fennel seedling production, while B represents the system boundary for the cradle-to-farm gate LCA of sea fennel production.

2.3.2. Cultivation phase

The sea fennel is grown on an open field using standard agricultural practices on a 2.5 ha field surface. In the first year of production, the producer prepares the land by weeding and harrowing utilizing a milling machine. The land surface is covered with a plastic mulch, which is held in place by metal pegs to prevent removal by strong winds. On average, 40000 seedlings per ha are transplanted. Irrigation is not required, as it can negatively affect the sensory quality of the sea fennel. The life span of the plastic mulch and metal pegs was estimated to be six years. The cultivation systems do not require the application of agrochemicals like fertilizer, pesticides, and herbicides (by experience and tests in the open field, there was no difference between treated plants with organic fertilization and not treated ones). Sea fennel cultivation follows a seasonal cycle. Planting typically occurs between October and November. Harvesting takes place in the second year, starting in late May and extending through June and early July. During this period, mature sea fennel (young leaves and shoots) are hand-harvested into plastic crates and transported to a processing facility. The plants then regenerate, producing new vegetative growth and reaching full flowering by August. No further management is required until January. In the dormant winter

Table 1

Life cycle inventory to produce 1 p sea fennel seedlings.

	Quantity	Unit	Data source
Input			
Land size	1.50E-03	m^2	Primary
Soilless substrate (blonde peat)	3.75E-05	m^3	Primary
Vermiculite	4.50E-04	kg	Primary
Plastic seedling tray (polypropylene)	1.00E-04	kg	Primary
Water (irrigation)	1.00E-04	m^3	Primary
Polyvinyl chloride pipes (irrigation)	3.57E-05	kg	Primary
Chromium steel pipes (greenhouse arches)	2.26E-04	kg	Estimated
Polyethylene, low density (greenhouse cover)	4.67E-04	kg	Estimated
Product output			
Seedlings	1	p	Primary

months, when temperatures are low, the plants are cut at ground level. This encourages compact, well-standardized growth that will yield the finest harvest in April and May of the following season. Table 2 shows the inventory data used for sea fennel cultivation.

2.3.3. *Waste management*

Plastic waste management was modeled as 50% incineration, 30% recycling, and 20% landfilling. For the recycling, we considered 90% technological efficiency using the best available technology and 70% market substitutability of recovered plastic material, with the residue going to a sanitary landfill. Electricity, process water, and steam were considered 0.6 kWh, 2.6 kg, and 0.89 MJ per kg total weight of plastic waste processed. We assumed no losses during sorting as the materials were gathered and made ready for collection by the producer. However, we excluded the transportation of materials from the farm to the material recovery facility and any transportation after that. For metal (iron pegs) recycling, the electricity use considered was 0.50 kWh per kg of metal scraps processed and a process efficiency of 90%. We also assumed 10% losses of iron pegs on the field and during transportation. For sanitary incineration and landfilling, we selected proxy processes from the Ecoinvent database that covered the transport requirements from generating activities to the place of treatment.

Table 2

Life cycle inventory to produce 1 kg fresh sea fennel biomass.

	Quantity	Unit	Transport distance	Transport mode	Data source
Input					
Land size	1.25E-04	ha	–	–	Primary
Seedlings	8.33E-01	p	–	–	Primary
Tillage, currying (field operation)	2.08E-05	ha	–	–	Primary
Tillage, harrowing (field operation)	2.08E-05	ha	–	–	Primary
Weed control	8.08E-06	ha	–	–	Primary
Polypropylene (plastic mulch)	1.56E-02	kg	400 km	freight, lorry 16–32 t, euro 5	Primary
Steel, low-alloyed (metal pegs)	1.04E-03	kg	–	–	Primary
Polyethylene, high density (harvesting crate)	1.08E-03	kg	3.5 km	freight, lorry 16–32 t, euro 5	Primary
Product output					
Sea fennel, fresh weight	1	kg	–	–	Primary
Waste					
Ferrous metal scrap	1.04E-03	kg	–	–	Primary
Plastic mulch to waste treatment plant	1.72E-02	kg	–	–	Primary

2.4. *Interpretation*

The midpoint characterization results per the two selected functional units of 1 kg of sea fennel ("cradle-to-farm gate) and 1 p sea fennel seedling ("cradle-to-nursery gate) are presented in this study. The interpretation of results includes contribution analysis of the phases and key processes (hotspot analysis) and sensitivity analysis. The LCIA results are normalized and expressed in units of Person equivalent (PE) based on the total impact of a reference region for a certain impact category in the EF 3.0 method. Each Person equivalent represents the amount of environmental impact that equals one Person's average yearly share of the total impact of a reference region for a specific impact category in 2010 (Sala et al., 2018). The life cycle impact analysis was based on average point estimates of parameter values. Therefore, uncertainty analysis could not be performed. For the sensitivity analysis, we conducted a local sensitivity analysis to assess the impact of varying key parameters on different categories by increasing the input values by 10% for one input at a time and calculating the corresponding result scores and sensitivity ratio (SR). A total of 18 parameters were tested and analyzed. A scenario analysis of plastic waste management was also evaluated. We considered the business-as-usual as the baseline scenario, which is 50% municipal incineration, 30% recycling, and 20% sanitary landfilling (Section 2.3.3). The alternative scenario prioritizes plastic waste recycling, aligning with the EU's goal of a 70% recycling rate by 2050 (Preka et al., 2022; Stegmann et al., 2022), and assumes 70% recycling, 20% incineration, and 10% landfilling. Making informed decisions about sustainable food choices also involves considering both environmental and nutritional aspects. To achieve this, we compared the environmental impact, specifically the climate change score, of sea fennel to other horticultural products. This comparison was based on functional units that combined micronutrient content with environmental impact, taking into account that sea fennel was rich in these nutrients. The functional units selected for this comparison were total phenolic content (expressed as kg CO_2 eq./mg Gallic Acid Eq./g dry matter), vitamin A (expressed as kg CO_2 eq./Vit. A Retinol Activity Eq. mg/100g dry matter per kg CO_2 eq.), and vitamin E (expressed as kg CO_2 eq./Vit E mg/100g dry matter).

3. Results and discussion

This section presents and discusses the midpoint LCIA results of sea fennel cultivation (3.1), sea fennel nursery (section 3.2), and normalized results (3.3). Details on the sensitivity of the model parameters and scenario analysis of plastic waste management are provided in sections 3.4 and 3.5, respectively. Section 3.6 compares the results with literature based on different functional units.

3.1. *Cradle-to-farm gate analysis (sea fennel cultivation)*

The total midpoint impact assessment scores of 1 kg sea fennel are reported in Table 3, with the corresponding contribution analysis. In general, the results obtained were relatively low compared with other horticultural products, mainly due to the limited and low inputs coupled with the high yield of sea fennel. The cultivation phase had the most significant environmental impact across most categories. The nursery phase contributed less than 15% to the total impact of all categories except for HTC (41%) and WU (13%). Waste management had the lowest overall impact, primarily due to credits received from recycling plastic and metal.

Concerning climate change, the total CC score was 6.82E-02 kg CO_2 eq./FU. The score can be attributed to the absence of agrochemicals and periodic field operations generally associated with greenhouse gas emissions and ammonia. Sea fennel requires no agrochemicals, such as fertilizer, pesticides, and herbicides, for its cultivation, as it is most flavourful when it grows under stressful abiotic conditions. Therefore, applying agrochemicals during sea fennel cultivation can reduce the

Table 3
The midpoint impact scores of 1 kg of freshly harvested sea fennel at the farm gate with contributions from the various inputs.

Impact category	Unit	Total	Farmland	Seedlings	Field operations	Plastic mulch	Iron pegs	Harvest crates	Transport mulch	Transport crates	Plastic recycling	Plastic incineration	Plastic landfill	Metal recycling
CC	kg CO_2 eq.	6.82E-02	0.00E+00	6.70E-03	2.28E-03	3.84E-02	2.42E-03	4.06E-03	2.60E-04	9.45E-07	−6.14E-03	2.05E-02	6.36E-04	−9.04E-04
OD	kg CFC11 eq.	3.49E-10	0.00E+00	5.42E-11	3.38E-11	1.72E-10	4.03E-11	4.27E-11	3.67E-12	1.34E-14	−1.30E-11	2.10E-11	1.50E-12	−7.07E-12
IR	kBq U-235 eq.	1.53E-03	0.00E+00	1.93E-04	2.66E-05	9.78E-04	8.74E-05	2.84E-04	3.02E-06	1.10E-08	−2.33E-05	7.55E-06	2.21E-06	−2.47E-05
POF	kg NMVOC eq.	1.73E-04	0.00E+00	1.17E-05	2.57E-05	1.28E-04	1.12E-05	1.39E-05	1.15E-06	4.19E-09	−2.24E-05	5.71E-06	7.55E-07	−3.33E-06
PM	disease inc.	1.83E-09	0.00E+00	1.69E-10	6.15E-11	1.54E-09	1.98E-10	1.62E-10	1.76E-11	6.40E-14	−2.87E-10	2.34E-11	9.81E-12	−7.07E-11
HTNC	CTUh	4.61E-10	0.00E+00	4.54E-11	9.85E-11	2.93E-10	9.89E-11	3.28E-11	3.24E-12	1.18E-14	−5.20E-11	6.98E-11	1.33E-12	−1.30E-10
HTC	CTUh	1.95E-11	0.00E+00	6.93E-12	1.39E-12	8.45E-12	1.76E-11	1.14E-12	1.05E-13	3.82E-16	−1.30E-12	1.78E-12	4.03E-14	−1.66E-11
A	mol H^+ eq.	1.88E-04	0.00E+00	1.47E-05	1.87E-05	1.52E-04	1.03E-05	1.66E-05	8.73E-07	3.18E-09	−2.60E-05	4.66E-06	4.85E-07	−4.02E-06
EF	kg P eq.	8.15E-06	0.00E+00	8.47E-07	1.98E-07	6.44E-06	1.10E-06	9.93E-07	2.04E-08	7.42E-11	−1.08E-06	6.12E-08	9.53E-09	−4.32E-07
EM	kg N eq.	5.39E-05	0.00E+00	3.02E-06	7.98E-06	2.89E-05	2.36E-06	3.27E-06	2.81E-07	1.02E-09	−5.01E-06	2.66E-06	1.14E-05	−1.04E-06
ET	mol N eq.	4.49E-04	0.00E+00	3.17E-05	8.65E-05	3.07E-04	2.40E-05	3.40E-05	2.98E-06	1.08E-08	−5.27E-05	2.27E-05	1.86E-06	−8.54E-06
ETF	CTUe	1.41E-01	0.00E+00	1.07E-02	1.44E-02	1.00E-01	2.59E-02	1.07E-02	2.13E-03	7.76E-06	−1.82E-02	3.89E-02	2.47E-03	−4.63E-02
LU	–	6.31E+01	6.27E+01	2.38E-01	2.38E-01	9.49E-03	6.34E-02	8.08E-03	1.37E-02	1.82E-03	6.62E-06	−7.07E-03	1.16E-03	3.15E-03
WU	m^3 depriv.	1.57E-02	0.00E+00	4.71E-03	1.14E-04	6.91E-03	2.53E-04	9.15E-04	1.49E-05	5.42E-08	9.93E-04	9.31E-04	5.83E-05	8.39E-04
RUF	MJ	1.23E+00	0.00E+00	1.03E-01	2.86E-02	1.19E+00	2.53E-02	1.02E-01	3.50E-03	1.27E-05	−2.20E-01	3.77E-03	1.40E-03	−8.75E-03
RUM	kg Sb eq.	1.82E-07	0.00E+00	3.14E-08	9.79E-09	1.42E-07	1.51E-08	1.23E-08	7.94E-10	2.89E-12	−2.71E-08	9.83E-10	1.45E-10	−3.18E-09

CC – climate change estimated over a 100-year horizon, OD – ozone depletion, IR – ionizing radiation, POF – photochemical ozone formation, PM – particulate matter, HTNC – human toxicity, non-carcinogenic, HTC – human toxicity, cancer, A – acidification, EF – eutrophication freshwater, EM – eutrophication marine, ET – eutrophication terrestrial, ETF – ecotoxicity freshwater, LU – land use, WU – water use, RUF – resource use, fossils, and RUM – resource use, minerals, and metals.

quality of the final product without any substantial increase in yield, resulting in reduced environmental performance. Plastic mulch (47%) and its incineration (25%) significantly contributed to the CC score. This is likely due to the high amount of polypropylene used, a fossil-based plastic with a short lifespan (around six years). Seedlings contributed 8% while harvesting crates contributed 5% due to their long life span (10 years) and reuse. The 30% recycled plastic resulted in a 7.5% credit from the avoided production of an equivalent virgin plastic.

The water use impact was 1.57E-02 m^3 water eq. of deprived water, which is relatively low when compared to other vegetables (Frankowska et al., 2019). This can be attributed to the absence of irrigation and the minimal water requirements for seedling watering. The main factors contributing to this impact were linked to plastic mulch production and the associated background processes. Significant water-saving opportunities are inherent in sea fennel cultivation. The plant requires minimal water resources since arid conditions enhance its flavor. Additionally, the absence of irrigation negates the need for water distribution systems and the energy typically consumed in pumping and delivering water. In regions affected by drought and water scarcity, sea fennel has the potential to offer a viable solution to address food and feed shortages.

Regarding the other impact categories, plastic mulch emerged as the leading contributor mainly due to the substantial amount of material used and the energy required for plastic production. The absence of agrochemicals also positively affected the impact scores. However, noteworthy contributions include nursery irrigation (30%) in the case of WU and iron pegs (32%) for HTC. Metal recycling, leading to the avoided production of steel, resulted in substantial gains in HTC (30%), HTNC (16%), and ETF (17%). In contrast, metal recycling resulted in a 5% increase in WU's score. The sea fennel had a good environmental performance under a sustainable farming system that excludes agrochemical use. Similarly, organic food products have been associated with several environmental benefits, including climate change and other impacts. However, in certain instances, yields may be determined by factors like low soil fertility and susceptibility to pests and diseases when crops lack resistance (Boakye-Yiadom et al., 2023).

As mentioned earlier, plastic mulch was the primary contributing input for all the impact categories except for HTC and LU. Plastic mulch is vital in sea fennel production because it contributes to several aspects, including weed control, soil moisture and temperature regulation, reduced soil erosion, pest and disease control, and reduced maintenance by avoiding periodic weeding. Consequently, while reducing fossil-based plastic could significantly reduce the impact results, finding an ideal substitute could be challenging. An attempt to use organic mulch in a field trial proved unsuccessful, as it failed to effectively suppress weed growth, leading to reduced sea fennel yields. Therefore, a potential mitigation approach could be substituting with soil-biodegradable plastics, which generally have a lower environmental footprint than fossil-based plastics (Spierling et al., 2020; Madrid et al., 2022). According to Tofanelli and Wortman (2020), soil-biodegradable mulches can provide comparable horticultural benefits, but their functions can differ widely between sites. In addition, plastic mulch made with recycled materials may be a more sustainable option than virgin plastic (Meys et al., 2020) since it does not have to be of the highest quality. Promoting plastic recycling as a part of broader efforts to establish a circular economy can enhance the overall environmental performance of sea fennel production. In the study, we considered a 30% recycling rate, which resulted in various benefits, including up to 18% credits due to the avoided production of virgin plastic. It is also important to note that the current impact assessment methods do not yet include microplastic pollution, which is an emerging global concern, particularly in coastal areas (Tang et al., 2021; Fischer et al., 2016; Zhang et al., 2020). In practice, it is not feasible to eliminate all mulch fragments from the field. The remaining remnants have the potential to degrade into micro- and nanoplastics, which may be transported into the soil through subsurface mechanisms (Yu and Flury, 2021). Therefore, a substantial reduction in the use of fossil-based plastics or substitution with bioplastics holds the potential for significant positive impacts on both sea fennel production and the environment and is also in line with organic agriculture.

3.2. *Cradle-to-nursery gate analysis (sea fennel seedlings)*

The impacts of the nursery phase are reported in Table 4. A large portion of the impacts for this phase were related to the greenhouse infrastructure comprising the metal arches and LDPE cover (Fig. 2). The two accounted for more than 70% of the total impacts across the various impact categories, excluding CC, OD, LU, WU, and RUF. The greenhouse for raising the seedlings is a simple structure with no use of a heating and lighting system. This explains the low-impact scores obtained. The other impacting input was the soilless substrate (Blonde peat), which made notable contributions to LU (68%), CC (60%) and RUF (48%). Peat moss is suitable for growing acid-loving crops such as sea fennel, resulting in higher seed germinability than soil. However, harvesting peat moss from the natural environment results in the release of stored carbon into the atmosphere and the potential degradation of peatlands (Harenda et al., 2018), thus explaining its contribution to these impact categories. While a small amount of peat moss is used in the nursery phase, its potential environmental impact is concerning. Therefore, exploring alternative, sustainable growing mediums like sphagnum moss (McKeon-Bennett and Hodkinson, 2021) and frass from insect-treated bio-residue is crucial. Furthermore, sterilization and reuse of peat moss is a viable option for reducing environmental impacts. Water from wells for irrigation also accounted for nearly 70% of the total impacts related to water use, while the polypropylene seed trays and PVC pipes for irrigation made minor contributions to the different impact categories.

3.3. *Normalized LCA results*

Normalization helps in understanding and interpreting the relative significance of diverse environmental impact categories. Additionally, normalized impact values offer guidance and aid in identifying target inputs, activities, and emissions where substantial benefits can be realized for each calculated impact. Fig. 3 shows the normalized LCIA results for the impact categories in the EF 3.0 LCIA methodology. LU had the highest normalized score, followed by RUF (Fig. 3). All other impact

Table 4

The midpoint impact scores of 1 p sea fennel seedlings produced per one greenhouse cycle.

Impact category	Unit	Score
CC	kg CO_2 eq.	8.05E-03
OD	kg CFC11 eq.	6.51E-11
IR	kBq U-235 eq.	2.32E-04
POF	kg NMVOC eq.	1.41E-05
PM	disease inc.	2.03E-10
HTNC	CTUh	5.45E-11
HTC	CTUh	8.31E-12
A	mol H^+ eq	1.77E-05
EF	kg P eq.	1.02E-06
EM	kg N eq.	3.62E-06
ET	mol N eq.	3.80E-05
ETF	CTUe	1.29E-02
LU	–	2.85E-01
WU	m^3 depriv.	5.65E-03
RUF	MJ	1.23E-01
RUM	kg Sb eq.	3.77E-08

CC – climate change estimated over a 100-year horizon, OD – ozone depletion, IR – ionizing radiation, POF – photochemical ozone formation, PM – particulate matter, HTNC – human toxicity, non-carcinogenic, HTC – human toxicity, cancer, A – acidification, EF – eutrophication freshwater, EM – eutrophication marine, ET – eutrophication terrestrial, ETF – ecotoxicity freshwater, LU – land use, WU – water use, RUF – resource use, fossils, and RUM – resource use, minerals and metals.

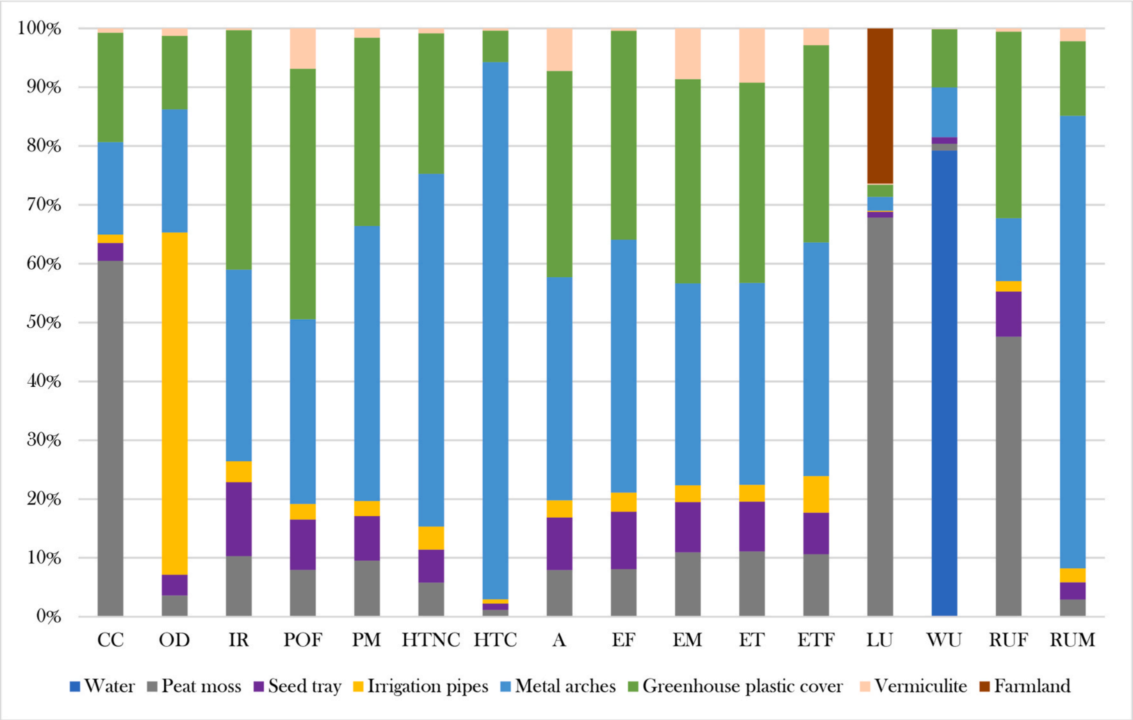

Fig. 2. The overall contribution of the various inputs for producing one sea fennel seedling cradle-to-nursery gate.
CC – climate change estimated over a 100-year horizon, OD – ozone depletion, IR – ionizing radiation, POF – photochemical ozone formation, PM – particulate matter, HTNC – human toxicity, non-carcinogenic, HTC – human toxicity, cancer, A – acidification, EF – eutrophication freshwater, EM – eutrophication marine, ET – eutrophication terrestrial, ETF – ecotoxicity freshwater, LU – land use, WU – water use, RUF – resource use, fossils, and RUM – resource use, minerals and metals.

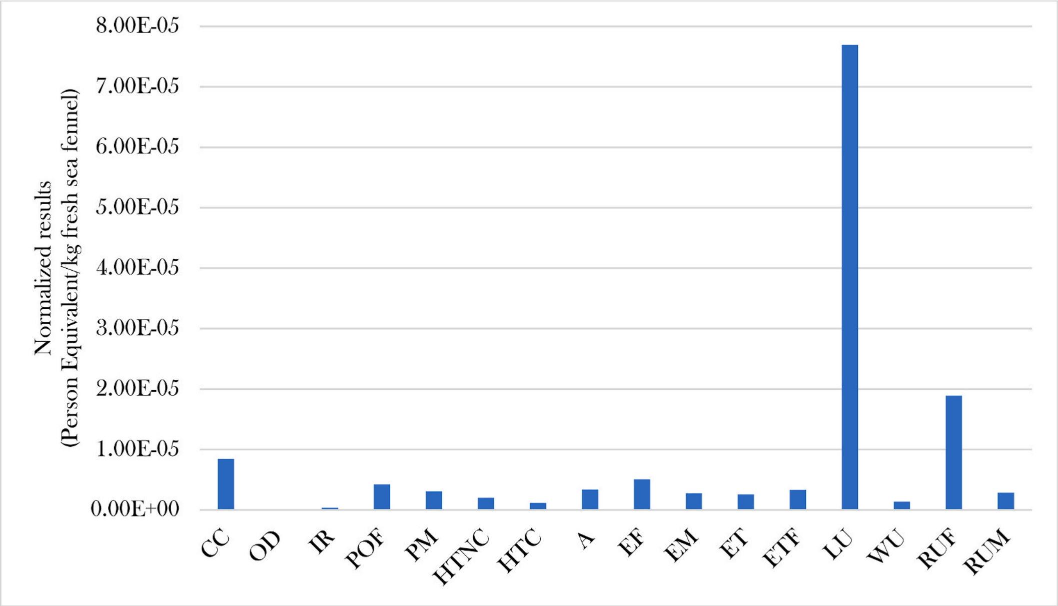

Fig. 3. Normalized results for sea fennel production, cradle-to-farm gate.
CC – climate change estimated over a 100-year horizon, OD – ozone depletion, IR – ionizing radiation, POF – photochemical ozone formation, PM – particulate matter, HTNC – human toxicity, non-carcinogenic, HTC – human toxicity, cancer, A – acidification, EF – eutrophication freshwater, EM – eutrophication marine, ET – eutrophication terrestrial, ETF – ecotoxicity freshwater, LU – land use, WU – water use, RUF – resource use, fossils, and RUM – resource use, minerals and metals.

categories had normalized scores lower than 1.00E-05 Person eq./kg sea fennel. Impact categories like OD and IR had negligible normalized scores. The high score for LU was related to the low productivity of sea fennel. The yield for sea fennel was about 8 tonnes/ha. The adaptability of sea fennel to thrive on marginal lands reduces competition for prime agricultural land. However, due to the absence of site-specific data, the LU results in this context could lead to overestimated environmental burdens. Land is a limited resource and in constant demand. Therefore, the opportunity cost of the land should be determined based on its characteristics to ascertain the best use or ways to improve productivity. Furthermore, indirect land use changes were not factored into the assessment. This was based on the observation that sea fennel production is currently limited to a relatively small cultivated area globally (about 80 ha) and has not sparked any substantial market changes or increased demand for land. The score for RUF was also linked to the production and use of fossil-based plastic materials (about 75%), mainly plastic mulch. A similar trend was observed for the other impact categories. For CC, seedlings and incineration of plastic waste contributed about 40% to the normalized score. While the normalized results are encouraging and may not require significant investments to reduce impacts, optimizing plastic usage could yield additional environmental advantages.

3.4. Sensitivity of model parameters

From the results of the perturbation analysis, the main sensitive parameters are plastic mulching, iron pegs, and peat moss. While most parameters exhibited negligible sensitivity ratios (SRs), generally below 0.2, the SRs did vary among different impact categories, with the highest not exceeding 0.75. None of the parameters were sensitive in RUF and RUM. Plastic mulch was the most sensitive parameter for all the impact categories. This can be attributed to the extensive usage of plastic mulch and the related background processes that influence other impact categories, resulting in relatively high SR scores, notably 0.71, 0.67, and 0.61 for PM, WU, and CC, respectively. Peat moss significantly influenced LU (0.42), while iron pegs recorded SR scores of 0.47 and 0.29 for HTC and HTNC. Local sensitivity analysis is crucial for identifying parameters that significantly affect results when subjected to minor variations. It helps determine where resources should be invested to collect precise data. However, it is important to note that perturbation analysis does not provide insights into the degree of uncertainty associated with the final results since it does not reflect the actual input uncertainties. This study relied on point estimates obtained from the producer. While this approach provided valuable data, it limited our ability to perform a comprehensive uncertainty analysis alongside the sensitivity analysis.

3.5. Scenario analysis of waste management

Due to the relatively high impacts of the plastic mulch, we included a scenario analysis for plastic waste management. The leading waste technologies considered were recycling at a material recovery facility, municipal incineration, and sanitary landfilling. The results show that increasing the recycling rate from 30% to 70% can improve the environmental performance of sea fennel cultivation (Fig. 4). There were reductions in impact scores of up to 33% for the various impact categories, except for WU, which recorded a 5% increase in score. This increase was due to the rise in water, steam, and electricity demand for plastic recycling at the material recovery facility. ETF and CC had the highest reductions of 33% and 30%, respectively, due to the avoided production of fossil-based plastics. Among the selected waste management technologies, recycling is the most preferred, followed by incineration and landfilling, as stated in the Waste Framework Directive 2008/98/EC (European Parliament, 2008). While the incineration of plastics can generate fuel energy due to their high calorific value, the process also emits harmful pollutants such as carbon monoxide and polycyclic aromatic hydrocarbons, contributing to ozone damage (Lamont, 2005; Kasirajan and Ngouajio, 2012; Steinmetz et al., 2016). On the other hand, landfilling is a commonly used waste disposal method. Yet, the decreased available land and the release of hazardous by-products raise significant environmental concerns (Steinmetz et al., 2016; Yaashikaa et al., 2022). Increased recycling coupled with reduced incineration and landfilling often results in improved environmental performance of products. Considering that the producer prepares the waste for collection, practically all the plastic can be recycled. Furthermore, variations in the technical substitution ratio and the market displacement rate influence the total amount of virgin material displaced. Technological advancement can improve the technical substitution ratio in plastic recycling. However, including transportation and other logistics would also reduce the credits gained depending on the location of the waste management facilities and means of transport. It is also important to acknowledge that while recycling plastic mulch

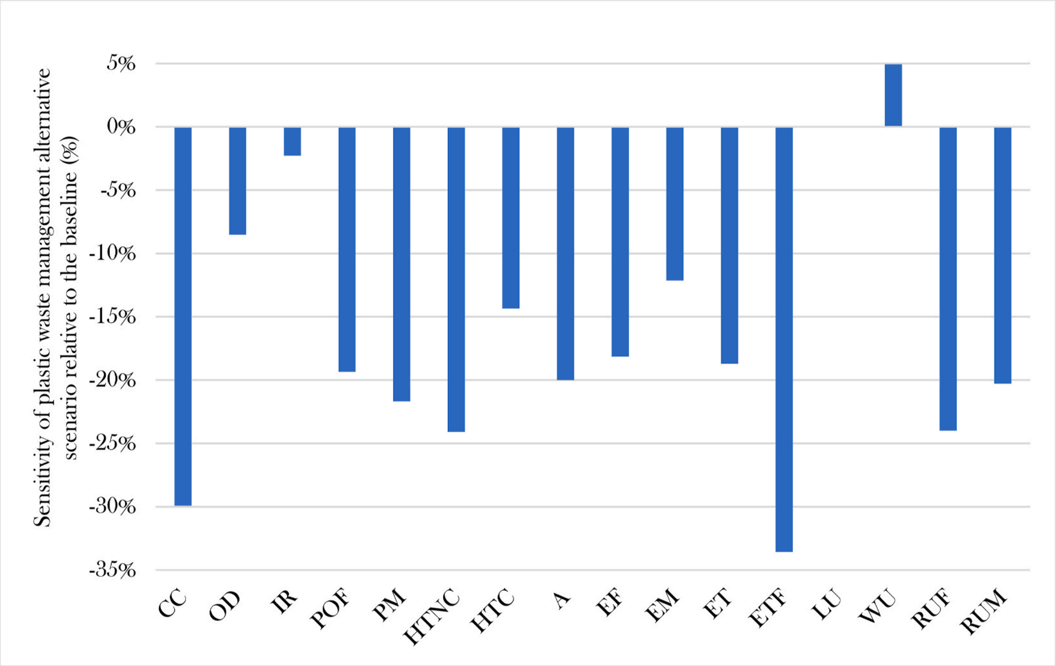

Fig. 4. The relative difference in the environmental performance of the alternative scenario (70% plastic waste recycling, 20% incineration, and 10% landfilling) to the baseline scenario (30% plastic waste recycling, 50% incineration, and 20% landfilling).
CC – climate change estimated over a 100-year horizon, OD – ozone depletion, IR – ionizing radiation, POF – photochemical ozone formation, PM – particulate matter, HTNC – human toxicity, non-carcinogenic, HTC – human toxicity, cancer, A – acidification, EF – eutrophication freshwater, EM – eutrophication marine, ET – eutrophication terrestrial, ETF – ecotoxicity freshwater, LU – land use, WU – water use, RUF – resource use, fossils, and RUM – resource use, minerals and metals.

can be a more sustainable option, cleaning and decontaminating used plastic mulch is expensive, and commercial technology is usually not accessible or economically viable in many regions due to the current economic and political climate (Madrid et al., 2022). Thus, the results indicate the need to invest in recycling plastic to achieve a circular economy.

3.6. Comparison with other studies

Sea fennel is a unique crop with uncertain functions due to its underexploitation and limited use. Commercially, it is used as a food preserve and, therefore, could function similarly to other food condiments. Botanically, it is classified under the Umbelliferae or Apiaceae family and shares close relations with crops like fennel, celery, parsley, parsnip, and wild carrot. Horticultural production can have significant environmental implications, given the intensive use of resources, such as land, water, agrochemicals, and labor. However, comparing LCA results proves challenging due to variations in modeling choices, system boundaries, and assumptions. To contextualize our findings, we compared our study results with available data on other cultivated species within the same family. Frankowska et al. (2019) conducted a life cycle assessment of vegetables consumed in the UK, including celery and carrots, comparing impacts between local production and imports. For CC, they reported higher CC scores of 0.19 kg CO_2 eq. per kg of locally produced and imported celery and 0.17 and 0.22 kg CO_2 eq. per kg, UK-produced carrot and imported carrot, respectively. Their assumption of conventional farming practices for the vegetables may explain the score differences. Additionally, carrots are a root vegetable that requires more field operations, especially for harvesting. Davis (2011) also reported comparable CC scores of 0.12 kg CO_2 eq. and 0.08 kg CO_2 eq. per kg parsnip and carrot, respectively, produced in an open field in Sweden under a conventional system. In other comparable impact categories such as WU, OD, POF, EF, and EM, the sea fennel consistently outperformed the reported values for celery and carrots by Frankowska et al. (2019), highlighting its superior environmental performance.

The primary function of foods is typically associated with macronutrients, which may not adequately capture the nutritional benefits of certain fruits and vegetables valued for their health-promoting compounds. For consumers prioritizing food consumption based on both nutraceutical attributes and environmental impact, it becomes crucial to integrate nutritional aspects into the environmental impact assessment of foods. This approach enables consumers to make well-informed decisions. In this study, we attempted to express the function of the sea fennel and other selected products based also on their nutraceutical properties. To provide a comprehensive understanding of the impact of sea fennel, we presented climate change results using various micronutrient-based functional units, moving beyond mass as the sole

Table 5
Content of total phenolic content, vitamin A, and vitamin E in selected sources.

Product	TPC (mg GAE/g dm)	Vit A (RAE mg/100 g dm)	Vit E (mg/100 g dm)	TPC refs.	Vit A refs.	Vit E refs.	CC score refs.
Sea fennel	2.6–56	0.5–2	20–53	(Meot-Duros and Magné, 2009; Veršić Bratinčević et al., 2023; Nartea et al., 2023; Souid et al., 2020; Houta et al., 2011; Kadoglidou et al., 2022)	Nartea et al. (2023)	Nartea et al. (2023)	This study
Spinach	12–68	4.7–7.3	–	(Lin and Tang, 2007; Bunea et al., 2008; NaTELla et al., 2010; Turkmen et al., 2005)	(Tang, 2010; Carazo et al., 2021)	–	(Foppa Pedretti et al., 2021; Frankowska et al., 2019; Theurl et al., 2017; Stoessel et al., 2012)
Green pea	1.73–7.6	–	–	(NaTELla et al., 2010; Turkmen et al., 2005)	–	–	(Boakye-Yiadom et al., 2023; Frankowska et al., 2019; Tidåker et al., 2021; Bandekar et al., 2022; Del Borghi et al., 2018)
Broccoli	3.1–21	–	–	(Turkmen et al., 2005; Koh et al., 2009; Lola-Luz et al., 2014; Jokić et al., 2012)	–	–	(Frankowska et al., 2019; Theurl et al., 2017; Ríos-Fuentes et al., 2022)
Strawberry	28–175	–	–	(Lin and Tang, 2007; Panico et al., 2009; Mahmood et al., 2012; Cervantes et al., 2020; Dzhanfezova et al., 2020)	–	–	(Parajuli et al., 2022; Peano et al., 2015; Tabatabaie and Murthy, 2016; Valiante et al., 2019; Gunady et al., 2012; Khoshnevisan et al., 2013)
Carrot	–	6–12.3	–	–	Carazo et al. (2021)	–	(Frankowska et al., 2019; Davis, 2011; Lopes et al., 2018)
Parsley	–	4.4–4.6	–	–	Carazo et al. (2021)	–	Ab, Ec, Wf
Lettuce	–	2.9–9.9	–	–	Carazo et al. (2021)	–	(Frankowska et al., 2019; Theurl et al., 2017), Ab, Ec, Wf
Chicory	–	6.6–12.2	–	–	Carazo et al. (2021)	–	Ab, Ec, Wf
Sunflower oil	–	–	32–71	–	–	Shahidi et al. (2021)	Ab, Ec, Wf
Olive oil	–	–	12–52	–	–	Shahidi et al. (2021)	Ab, Ec, Wf
Peanut oil	–	–	4.7–30	–	–	Shahidi et al. (2021)	Ab, Ec, Wf
Rapeseed oil	–	–	18.3–24	–	–	Shahidi et al. (2021)	Ab, Ec, Wf
Palm oil	–	–	6.1–42	–	–	Shahidi et al. (2021)	Ab, Ec, Wf

TPC – Total phenolic content, GAE – Gallic acid equivalent, Vit – Vitamin, RAE – Retinol activity equivalent, dm – dry matter, CC – climate change, Ab – Agribalyse version 3.1, Ec – Ecoinvent version 3.9, Wf – World Food LCA Database version 3.5.

metric. Table 5 and Fig. 5 show total phenolic content (TPC), vitamin A, and vitamin E content, along with their corresponding CC scores. These scores are derived from data obtained at the farm gate, from literature sources, and life cycle assessment (LCA) databases, including Agribalyse, Ecoinvent, and the World Food LCA database.

The results underscore the considerable variability in environmental impact depending on the chosen functional unit, specifically nutrients (Fig. 5). Overall, sea fennel exhibited lower climate change (CC) scores compared to other sources, though there was some overlap in results. The narrow and low ranges for sea fennel could be attributed to its relatively low impact scores and richness in the selected nutraceutical compounds.

As secondary metabolites, plant phenolic compounds provide properties that are beneficial to animal or human health, primarily due to their antioxidant activity. Examining the total phenolic content (TPC) results, sea fennel, spinach, and strawberry demonstrated comparable minimum scores of 0.02 kg CO_2 eq./mg GAE/g dm (Fig. 5a). Spinach outperformed sea fennel due to its lower CC score, ranging between 0.075 and 0.2 kg CO_2 eq./kg fresh spinach at the farm gate. Conversely, the score ranges were wider for green peas, broccoli, and strawberries, with broccoli exceeding 1 kg CO_2 eq./mg GAE/g dm. Vitamin A, an essential nutrient crucial for vision and cellular integrity, revealed varying performance results (Fig. 5b). Sea fennel outperformed only lettuce, which exhibited the widest variation in results. The maximum CC scores for sea fennel (1.14 kg CO_2 eq./Vit. A RAE mg/100 g d.m.) and lettuce (2.97 kg CO_2 eq./Vit. A RAE mg/100 g d.m.) were notably higher, signifying their relatively low vitamin A content. We calculated Vitamin E considering only α-tocopherol, following the proposal by the EFSA NDA Panel (EFSA Panel on Dietetic Products et al., 2015). As an essential lipophilic antioxidant, α-tocopherol protects lipoproteins, polyunsaturated fatty acids, cellular membranes, and intracellular compartments in humans. Thus, it is integral to the antioxidant defense system. Sea fennel, sunflower oil, olive oil, and rapeseed oil displayed relatively low impact scores, with sea fennel demonstrating the best performance (Fig. 5c). Although peanut and palm oil had minimum values comparable to the others, they had substantially wider ranges, with scores close to 0.9 kg CO_2 eq./Vit E mg/100 g d.m.

It is important to note that we reported ranges instead of mean values because of the challenge of comparing impact scores given the variability in assumptions and modeling choices. Due to the use of secondary data, reporting ranges provided a more accurate representation of the potential variability in actual environmental performance. Although LCA results were selected for open-field cultivated products, there can also be significant variations in scores related to geographical, technological, and time boundaries. Additionally, there is some uncertainty regarding the evaluated nutrients due to the differences in varieties and the analysis methods used. These limitations should be taken into account when interpreting the results.

4. Conclusion

This study employs the LCA methodology to assess the environmental performance of open-field sea fennel production in central Italy (Marche region). It represents one of the pioneering efforts to evaluate the environmental impact of cultivating sea fennel, an emerging crop with the potential to gain significance in the food and feed sectors. The potential environmental impacts according to the Environmental Footprint (EF) 3.0 midpoint life cycle impact assessment (LCIA) method are expressed per 1 kg fresh sea fennel (functional unit). The results of our study suggest that sea fennel cultivation shows a promising environmental profile due to its minimal use of agrochemicals and low water requirements. Consequently, sea fennel may serve as a suitable alternative to conventional crops, particularly in regions experiencing water scarcity, while still contributing to dietary needs. LU attained the highest score in the normalized results owing to its relatively low productivity in terms of yield per hectare. Nevertheless, considering sea fennel's capacity to thrive in marginal soils, this may not have significant environmental implications.

The primary environmental concern was the use of plastic mulch, which contributed substantially to the various impact categories. To

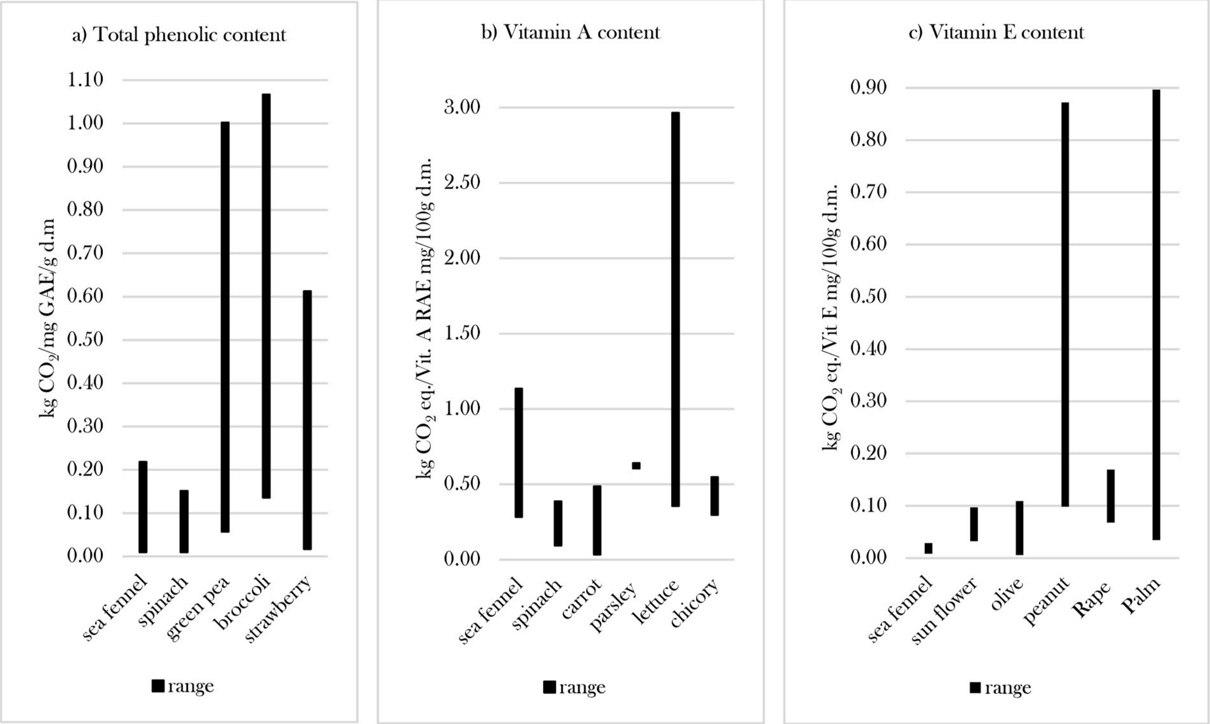

Fig. 5. Climate change score ranges reported for different food products based on nutritional content.
GAE – Gallic acid equivalent, Vit – Vitamin, RAE – Retinol activity equivalent, dm – dry matter.

mitigate this challenge, exploring sustainable alternatives to traditional plastic mulch, such as recycled plastic or other eco-friendly materials with similar functionality, is crucial. Waste management, mainly through enhanced recycling practices, plays a pivotal role in mitigating the environmental impact, considering the substantial plastic usage in sea fennel production. Increasing the recycling rate from 30% to 70% substantially improved the environmental performance of the sea fennel production. This underscores the importance of investing in plastic recycling initiatives to move closer to a circular economy.

For persons interested in nutritional LCA, the study also demonstrated substantial variations in environmental impact scores based on the selected functional unit, in this case, micronutrients. Integrating nutritional and environmental performance can help consumers make more informed dietary choices. Despite the ease of communicating single nutritional scores, specific weighting factors for micronutrients persist, especially for underutilized crops. Consequently, for minor crops primarily consumed for their health-promoting properties, distinct weighting factors will be essential for establishing a meaningful comparative basis.

However, the study is limited by the lack of foreground information on the waste management systems within the region, leading to the estimation of recycling rate and incineration and landfilling shares. It is worth mentioning that certain relevant environmental impact methods, such as microplastic pollution, are still being developed and are yet to be fully integrated into the LCA framework. Therefore, impacts related to plastic mulch may be underestimated. Future research should focus on sea fennel organic farming and on a comprehensive life cycle assessment of sea fennel products, extending beyond cultivation to encompass the entire supply chain, especially for food preserves. This holistic approach will provide a more accurate understanding of the environmental impact and inform targeted sustainability efforts.

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CRediT authorship contribution statement

Daniele Duca: Writing – review & editing, Visualization, Validation, Supervision, Investigation, Formal analysis, Data curation, Conceptualization. **Kofi Armah Boakye-Yiadom:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Alessio Ilari:** Writing – review & editing, Software. **Lucia Aquilanti:** Project administration, Funding acquisition. **Ester Foppa Pedretti:** Validation, Resources.

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.

Data availability

Data will be made available on request.

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