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Deliverable title	D8.1 Report on sustainability assessment of fresh sea fennel carried out by LCA from data collected thanks to WP4 activities
Deliverable Lead:	UNIVPM
Related Work Package:	WP8
Related Task:	Task 8.1 (D) Sustainability assessment of sea fennel open field production
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Summary of Deliverable D8.1 – Sustainability Assessment of Fresh Sea Fennel by LCA	This deliverable marks a turning point in understanding the environmental footprint of sea fennel cultivation. Using the internationally recognized Life Cycle Assessment (LCA) methodology (ISO 14040/44, EF 3.1), the consortium evaluated seedling production and open-field farming of sea fennel in central Italy, with results compared to other horticultural crops. The functional unit was 1 kg of fresh sea fennel at the farm gate, ensuring results were tangible and relatable. Findings are highly promising. Thanks to its minimal input requirements, sea fennel displayed a much lower environmental impact than many conventional vegetables. The crop thrives without agrochemicals and with very limited water use, which means reduced greenhouse gas emissions and strong suitability for drought-prone Mediterranean areas. Importantly, sea fennel actually benefits in quality when grown under mild stress, making low-input farming both ecologically and economically attractive. The main environmental hotspot identified was the use of plastic mulch, which accounted for nearly half of the climate change impact and contributed significantly across all categories. Scenario analyses revealed that increasing mulch recycling rates from 30% to 70% could reduce impacts by up to one third, highlighting the need for better recycling systems or alternatives such as biodegradable films. The study also flagged the environmental burden of peat substrates used in seedling nurseries, pointing to the need for more sustainable growing media. Overall, the assessment shows that sea fennel has a strong environmental profile compared to similar crops: low water footprint, no pesticide dependency, and resilience under organic systems. With targeted improvements in mulching materials and waste management, its sustainability can be further enhanced, aligning perfectly with the EU Green Deal, Farm to Fork, and circular economy strategies.

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Versioning and Contribution History

Version	Date	Modified by	Modification reason
V1.0	20/03/2023	Daniele Duca	First version
V2.0	30/03/2023	Daniele Duca	Comments after peer reviewing process
V3.0	30/09/2023	Daniele Duca	Update with results
V4.0	03/06/2024	Daniele Duca	Update with interpretation

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1. Report on sustainability assessment of fresh sea fennel carried out by LCA from data collected thanks to WP4 activities.

1.1 Introduction

According to the project's WP4, selected ecotype(s) will be assayed in an industrial-scale open field at an Italian farm with expertise in cultivating sea fennel (P3).

The life cycle assessment of sea fennel production will focus on the abovementioned trials because the scale is the same as the commercial situation, and the environmental sustainability indicators will be more consistent and comparable to those of other studies on similar products.

The technical documents needed to apply LCA methodology on the fresh sea fennel correctly have been checked and used as reference for the analysis (ISO 14040, ISO 14044, EPD PCR 2020:07).

A specific meeting has been held with P3 to plan the data collection needed to calculate the environmental indicators using LCA. The data collection file has been developed in interaction between P1 and P3 and completed by P3 during the open field trials. Another specific meeting was held to discuss the inventory and verify the data's consistency with the goal and scope. Based on this meeting, the inventory was modified, and missing data were made available. The life cycle impact assessment was performed to obtain preliminary results. A subsequent meeting has been held for discussion and interpretation based on the results obtained.

1.2 Life Cycle Assessment Method Overview

Life Cycle Assessment is currently used to assess the environmental sustainability of products and services considering their life cycle. The use of LCA is widely spread both in business and in decision-making contexts. Life Cycle Thinking (LCT) and LCA are commonly applied to agri-food and bioenergy products in different contexts (e.g., business and policymaking, and with different purposes, such as supporting strategic decisions to improve environmental performance and communication). Due to the complexity of the topic, different technical documents produced at different levels are used to drive the analysis. At the highest level, the ISO standards of the 14000 family are devoted to environmental issues and include ISO 14040 and ISO 14044. These standards are the reference documents for LCA, including principles, frameworks, requirements, and guidelines to drive LCA practitioners.

LCA – based on the LCT approach - addresses the environmental aspects and the potential environmental impact throughout a product's life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal. According to ISO standards, the assessment of the potential impact through LCA is based on a four-step, iterative procedure (see Fig. 1).

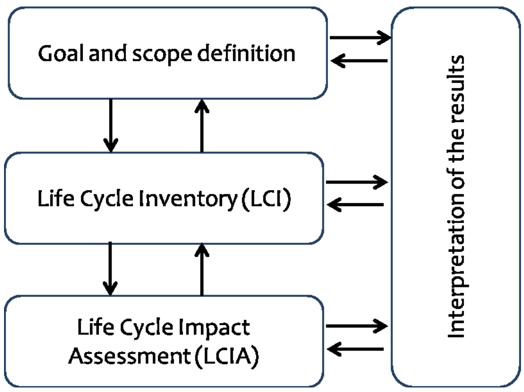

Fig. 1 – LCA framework according to ISO

The definition of goal and scope consists of the description of the product system under analysis, including the definition of system boundaries (mainly the phases of the supply chain included in the analysis with the related inputs and outputs) and the functional unit (FU), the unit to which the results of the study are referred. Other elements are the description of the reasons why the study was carried out and any deviation from the ISO standards. Furthermore, in this first step of the LCA, another important element to be defined is the choice of the allocation criteria (how to allocate impacts between products and coproducts). All the above-mentioned assumptions are reported for transparency in this first step to avoid any misunderstanding of the LCA results and to improve the possibility of comparing.

The life cycle inventory (LCI) is the step in which data collection is planned and realized. It consists of defining and quantifying all input and output flows entering and exiting the product system under analysis. When available, primary data collected directly from the supply chain stakeholders should be preferred. If this is not possible, secondary data reported in databases and scientific literature or even tertiary data (e.g., from estimates) can be used. The use of secondary datasets is a common practice in LCA when primary data are unavailable or their collection is not possible. Today, LCA is widely used, and internationally accepted LCA databases are now available for good secondary data. The result of LCI is the so-called inventory table, where all inputs, outputs, and emissions are reported with respect to the chosen FU.

The life cycle impact assessment (LCIA) step includes the characterization of the results, namely the quantification of the potential environmental impacts associated with resources used and emissions generated within the supply chain. This is obtained by multiplying each input and output flow by a characterization factor that expresses the extent to which a certain substance contributes to a certain environmental impact or impact category. For each impact category, the characterization factors are defined through the application of characterization models that should be scientifically and technically valid and link the substances to their potential impact. There are different LCIA methods based on distinct, identifiable environmental mechanisms or reproducible empirical observations carried out by researchers in the last decades on different impacts.

The final step is the interpretation of the results to check if they satisfy the aim or the aims of the study stated in the goal and scope section. Different checks are carried out in this final step until all four steps are considered consistent with each other and in line with the goal and scope. If a step is not consistent, this entails the iteration of the LCA until consistency is reached throughout the study.

Despite setting different pillars, the ISO standards are not focused on a specific product category, and additional documents are needed to limit the freedom of the practitioner and make the results more useful and comparable for similar products. For these reasons, other documents, in addition to the ISO standards, have been created by different bodies to be more specific for certain product categories.

One of the most interesting for the aim of task 8.1 is EPD PCR 2020:07. The document constitutes Product Category Rules (PCR) for arable and vegetable crops, developed in the framework of the International EPD System: a program for type III environmental declarations according to ISO 14025:2006. Although not specific to sea fennel cultivation, the document gives many indications on how to perform an LCA on crop cultivation and has been considered a reference.

Based on the abovementioned documents, the following choices have been made for LCA of fresh sea fennel:

- Functional Unit: 1 kg of fresh sea fennel (specifying moisture content and nutrients)
- System boundary: up to the fresh sea fennel harvested at the field (transportation to the processing plant is not included)
- The technical system shall not include personnel's business travel, travel to and from work by personnel, research and development activity, or buildings.

Based on the abovementioned documents, the following aspects were considered in the LCA of fresh sea fennel production:

- Production of inputs used for sea fennel cultivation (agrochemicals, if any, seeds, seedlings)
- Production of materials used for greenhouses, mulching, trays, and substrates (peat or others). Particular attention has been paid to mulching material.
- Production of electricity and fuels used, if any
- Production of auxiliary products used, if any
- Manufacturing of primary and secondary packaging, if applicable
- Transportation of inputs and materials to the cultivation field
- Amounts of inputs of energy and materials used for cultivation

- Direct emissions from sea fennel cultivation
- Preparation of the final product (before transportation), if any
- Waste treatment of waste generated during cultivation (e.g., mulching materials)
- Production of agricultural machinery

Primary data was collected from P3, and secondary data from LCA databases (Ecoinvent version 3.9, Agrifootprint, Agribalyse, World Food LCA database, etc.) and scientific literature.

The impact assessment was evaluated, highlighting the most important impact indicators (e.g., global warming, terrestrial acidification, freshwater eutrophication, fossil resource scarcity, abiotic depletion) from a selected life cycle impact assessment method using the SimaPro LCA software.

All the considerations reported above will be reviewed according to the interpretation step of the first LCA iteration.

1.3 Data and System Description

Goal and scope definition

The goal is to quantify the potential environmental impacts of sea fennel cultivation in Italian farms under an open-field production system, highlighting the environmental hotspots and opportunities for improvement. The cultivation is carried out on a 2.5 ha arable field located in Camerano, Marche region.

The system boundary we considered for this phase encompasses all the inputs in terms of materials and energy previously listed. The data collected is in reference to 2019. 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 – 2025. Additionally, we set up another functional unit of 100 sea fennel seedling per one cycle of greenhouse at the nursery gate.

The assessment covers the nursery phase, where the sea fennel seedlings are produced, and the cultivation phase. The nursery is situated on a 60 square meter area located near the farm and consists of a greenhouse-like structure. Basically, several metal arches are covered with a plastic film. The nursery has a capacity to produce about 40000 viable sea fennel seedlings per cycle. All inputs for producing the seedlings considered in the assessment and based on available data are shown in Fig. 2 and Table 1. However, where data was unavailable, especially pertaining to the greenhouse structure, estimations were made. Transportation of inputs was also excluded.

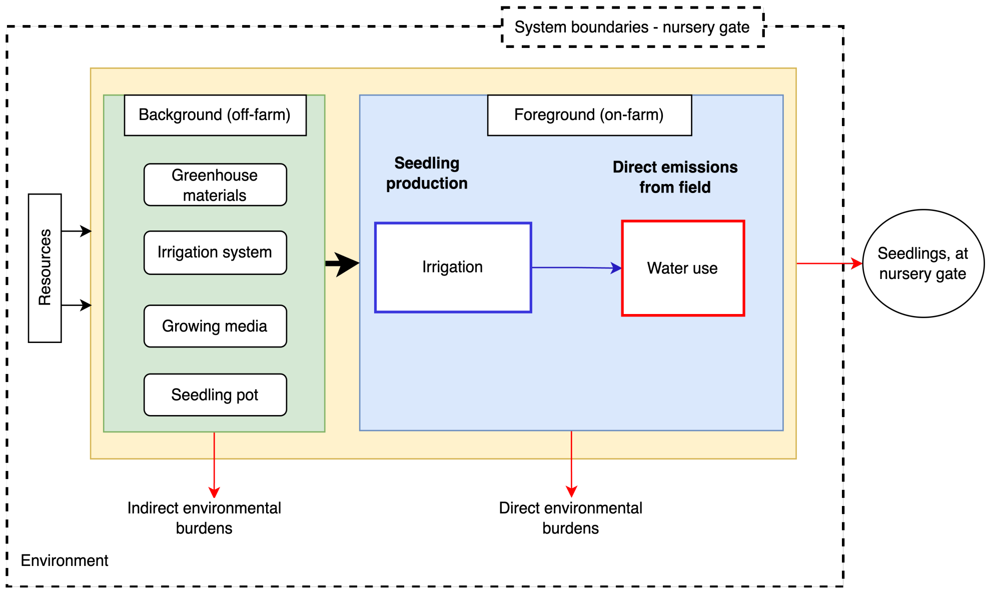

Fig. 2: The system boundary for the cradle-to-nursery gate LCA of sea fennel seedling production.

Table 1: Life cycle inventory to produce 100 sea fennel seedlings.

	Quantity	Unit	Data source
Input			
Land size	1.50E-01	m^2	Primary
Soilless substrate (Blonde peat)	3.75E-03	m^3	Primary
Vermiculite	4.50E-02	kg	Primary
Plastic seedling tray (polypropylene)	1.00E-02	kg	Primary
Water (irrigation)	1.00E-02	m^3	Primary
PVC pipes (irrigation)	3.58E-03	kg	Primary
Chromium steel pipes (greenhouse arches)	2.26E-02	kg	Estimated
Polyethylene, low density (greenhouse cover)	4.68E-02	kg	Estimated
Product output			
Seedlings	100	p	Primary

Regarding the cultivation phase, the sea fennel is grown using standard agricultural practices. The farmers conduct field operations, mainly harrowing in the first year of production. On average, the seedling quantity sown is about 40000 seedlings per ha. Seedlings are transported by a handcart. Irrigation is also not required, as it can negatively affect the sensorial quality of the sea fennel. The land surface is covered with a plastic mulch, which is held in place by metal pegs to prevent removal by strong winds. The life span of the plastic mulch and metal pegs was estimated to be six years. The cultivation systems could be considered organic since no application of agrochemicals like fertilizer, pesticides, and herbicides is required. Matured sea fennel is harvested by hand and put into plastic harvesting crates. Table 2 shows the collected inventory data used, while Fig. 3 shows the system boundary of the sea fennel cultivation.

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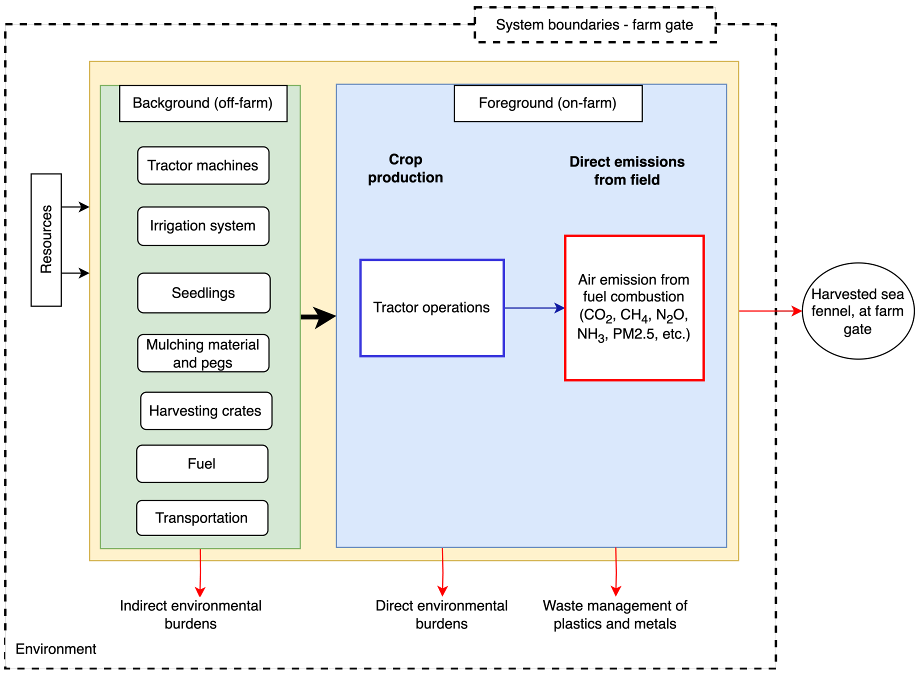

Fig. 3: The system boundary for the cradle-to-farm gate LCA of sea fennel production.

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, bush cutter (field operation)	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	-	-	Estimated
Polyethylene, high density (harvesting crate)	1.08E-03	kg	3.5 km	freight, lorry 16-32 t, euro 5	Estimated
Product output					
Sea fennel, fresh weight	1	kg	-	-	Primary
Waste					
Plastic to waste management	1.04E-03	kg	-	-	Primary
Metal to waste management	1.72E-02	kg	-	-	Primary

Life Cycle Impact Assessment and Interpretation

The impacts of the sea fennels, per the selected functional units, will be evaluated in terms of selected relevant impact categories using a recognized life cycle impact assessment (LCIA) methodology. Midpoint impact scores will be provided together with the relative contribution analysis to identify the critical hotspots and impacting processes, materials, or substances. Based on the results, relevant sensitivity analysis will be carried out to ensure the robustness and reliability of the LCA results. A comparison of impact scores will also be made with other similar products. Finally, mitigation strategies will be proposed to improve the overall environmental performance of sea fennel.

1.4 Main Findings

Cradle-to-farm gate analysis (sea fennel biomass)

The total midpoint impact assessment scores of 1 kg sea fennel are reported in Table 3, with the corresponding contribution analysis (see Fig. 4). 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 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 of deprived water due 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 eliminates the need for water distribution systems and the energy typically consumed in pumping and delivering water. Thus, 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. 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. 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 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. 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, an emerging global concern, particularly in coastal areas. 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.

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 (see Fig. 4).

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	Score
CC	kg CO_2 eq.	6.82E-02
OD	kg CFC11 eq.	3.49E-10
IR	kBq U-235 eq.	1.53E-03
POF	kg NMVOC eq.	1.73E-04
PM	disease inc.	1.83E-09
HTNC	CTUh	4.61E-10
HTC	CTUh	1.95E-11
A	mol H^+ eq	1.88E-04
EF	kg P eq.	8.15E-06
EM	kg N eq.	5.39E-05
ET	mol N eq.	4.49E-04
ETF	CTUe	1.41E-01
LU	-	6.31E+01
WU	m^3 depriv.	1.57E-02
RUF	MJ	1.23E+00
RUM	kg Sb eq.	1.82E-07

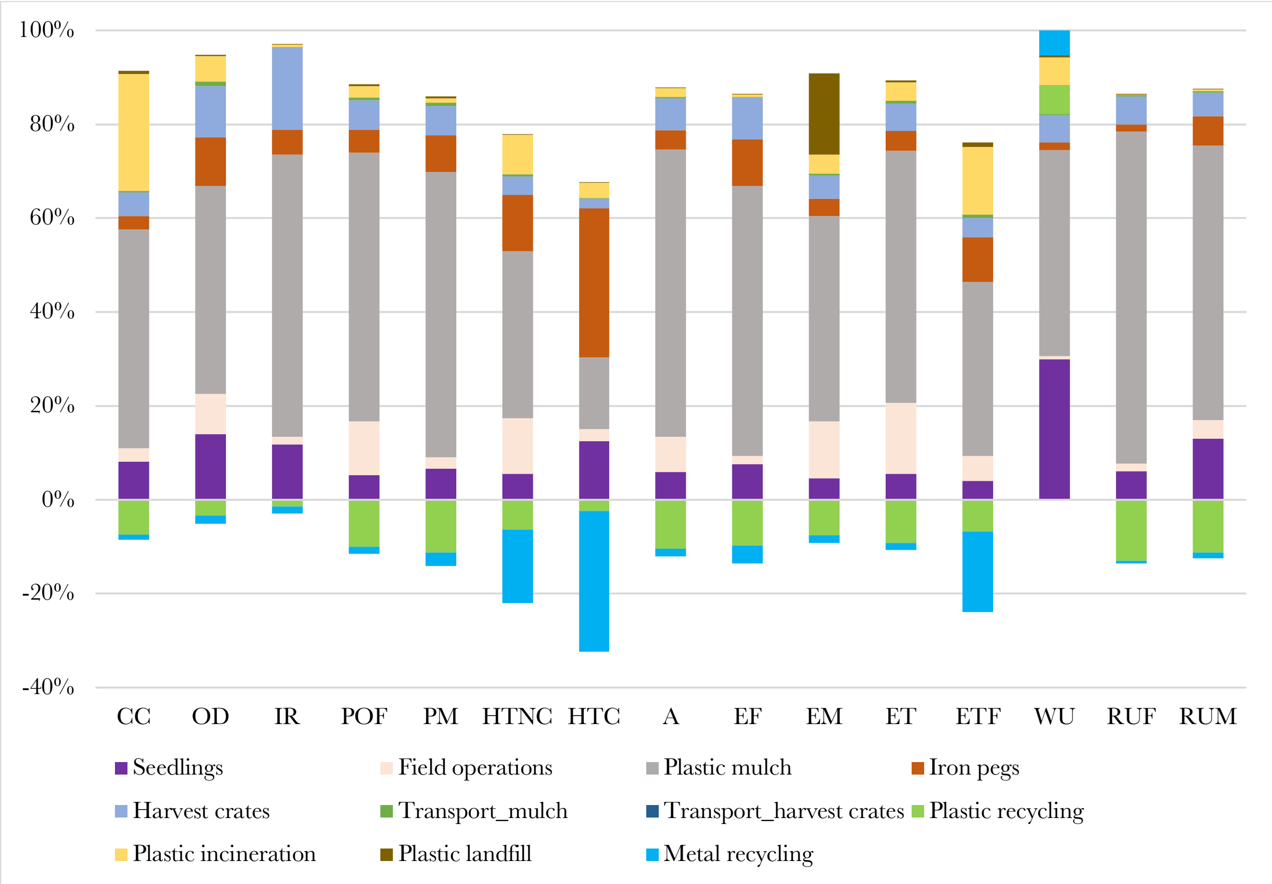

Fig. 4. The relative contribution of the various inputs for producing 1 kg sea fennel.

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. 5). 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, thus explaining its contribution to these impact categories. While a small amount of peat moss is used in the nursery phase, its possible environmental impact is concerning. Therefore, exploring alternative, sustainable growing mediums like sphagnum moss and frass from insect-treated bio-residue is crucial. Furthermore, sterilizing and reusing 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.

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

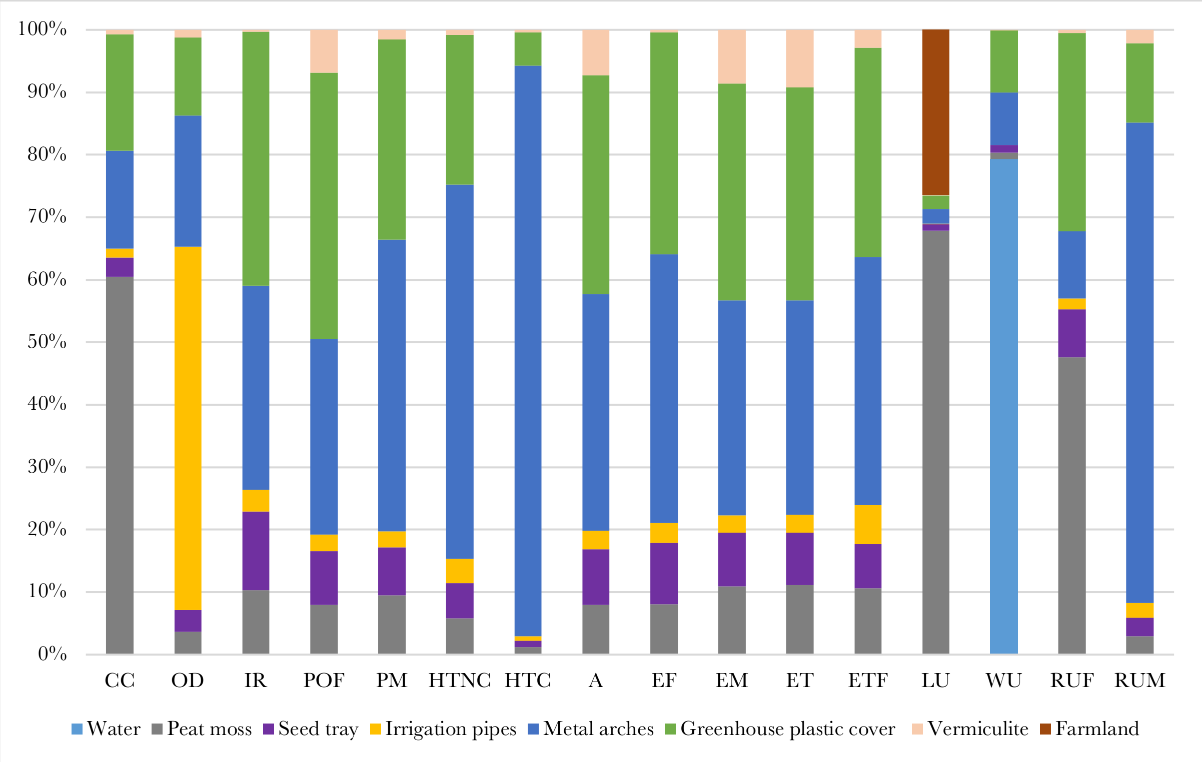

Fig. 5. The relative contribution of the various inputs for producing one sea fennel seedling.

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 (see Fig. 6). 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. 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 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. Thus, the results indicate the need to invest in recycling plastic to achieve a circular economy.

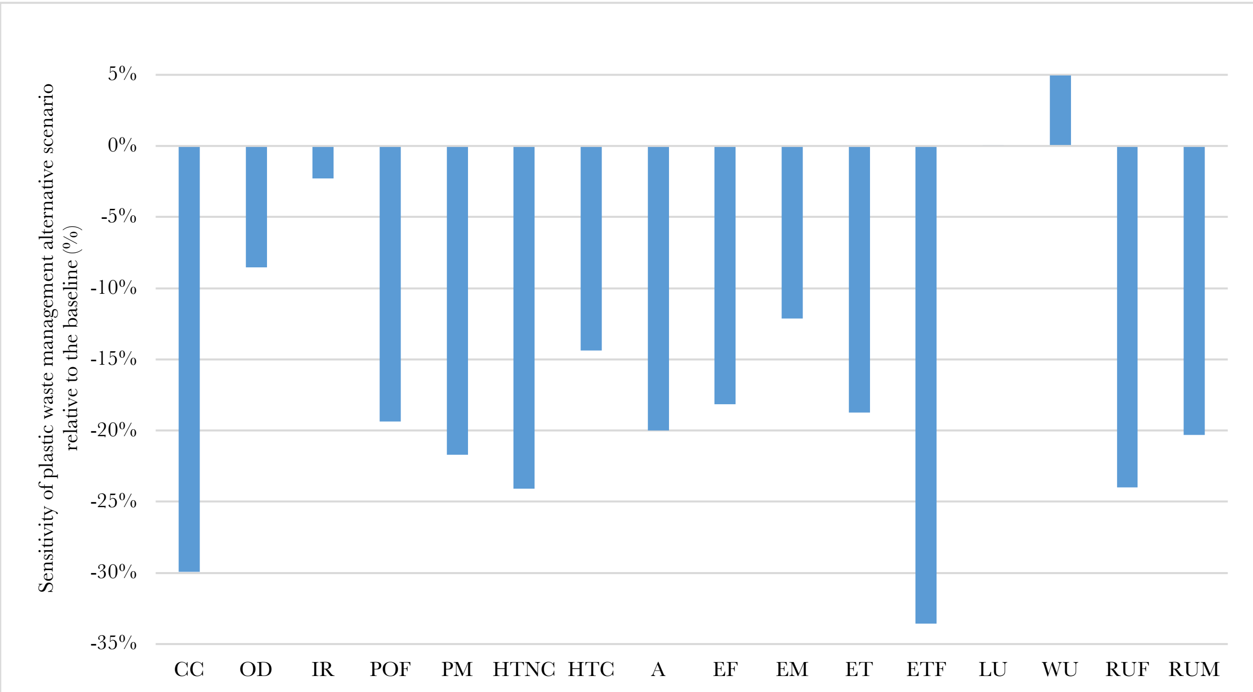

Fig. 6. The relative difference in the environmental performance of the alternative scenario (70 % plastic waste recycling, 20 % incineration, and 10 % landfilling) to the baseline scenario (30 % plastic waste recycling, 50 % incineration, and 20 % landfilling).

1.5 Conclusion

The environmental performance of open-field sea fennel production in central Italy (Marche region) was assessed following the LCA methodology. The potential environmental impacts based on the Environmental Footprint (EF) 3.1 midpoint LCIA method are expressed per 1 kg fresh sea fennel (functional unit).

Sea fennel cultivation showed 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 contributing to dietary needs. The primary environmental concern was using plastic mulch, which contributed substantially to the various impact categories. To 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. It is also 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. This further underscores the importance of investing in plastic recycling initiatives to move closer to a circular economy. Future research should focus on sea fennel organic farming and 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.

Most of the results obtained in task 8.1 have been published in an international peer reviewed journal in the following research paper:

Duca, D., Boakye-Yiadom, K. A., Ilari, A., Aquilanti, L., & Pedretti, E. F. (2024). Life cycle assessment of open field sea fennel production in central Italy. Cleaner Environmental Systems, 100198. https://doi.org/10.1016/j.cesys.2024.100198