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Summary of Deliverable D8.2 – Sustainability Assessment of Processed Sea Fennel Products by LCA	To evaluate the sustainability of its innovative food products, SEAFENNEL4MED applied the Life Cycle Assessment (LCA) method to two prototypes: dried sea fennel spice and fermented pickled sea fennel. The analysis considered the entire production chain - cultivation, processing, packaging, and waste management - making it possible to identify hotspots and improvements before full-scale commercialization. Findings showed that packaging was the dominant source of environmental impact, particularly glass jars and bottles. For both spice and pickles, glass accounted for more than half of the impacts in key categories such as climate change, acidification, and particulate matter. While glass is valued for its safety, recyclability, and consumer appeal, its heavy weight and energy-intensive production make it a challenge. Alternative strategies such as lighter packaging, refill systems with sachets, and higher recycling rates were shown to dramatically reduce impacts - by up to 44% in scenario analyses. Energy use was another hotspot, especially in the drying process for spice production, which requires several days at controlled temperatures. Transitioning to renewable energy sources (e.g., solar power) could reduce impacts by more than 10%, though with trade-offs in resource depletion linked to photovoltaic panel production.

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	For pickled products, the study compared two preservation methods: brine stabilization (requiring cold storage) and pasteurization (shelf-stable at room temperature). While pasteurization consumed more water, it eliminated the need for refrigeration during distribution and retail, significantly lowering long-term energy use and improving export potential. The choice of lid material (steel vs. aluminium) also influenced results, with aluminium offering slight environmental advantages in non-pasteurized products.

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	25/01/2025	Daniele Duca	Complete version before final check

Table of Contents

1. Report on sustainability assessment of processed sea fennel products carried out by LCA from data collected thanks to WP5 activities

1.1 Introduction

According to WP5, once the new organic crops became available, they were processed by P3 to produce pilot-scale prototypes of new sustainable foods or food ingredients. These prototypes were subsequently subjected to various tests to assess their nutritional, sensory, and functional properties.

The Life Cycle Assessment (LCA) of these new sea fennel foods is focused on the abovementioned trials because the scale is the same as the commercial situation, and the environmental sustainability indicators are more consistent and comparable to other studies on similar products.

The technical documents needed to apply LCA methodology on the sea fennel preserves have been checked and used as reference for the analysis (ISO 14040, ISO 14044, EPD PCR 2019:10 VERSION 2.0).

A specific meeting has been held with P3 to plan the data collection needed to calculate the environmental indicators by means of LCA. The data collection has been constructed in interaction between P1 and P3 based on sea fennel preserve production trials.

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 policy-making, and other purposes, such as support to strategic decisions to improve their environmental performance and environmental 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 (Figure 1).

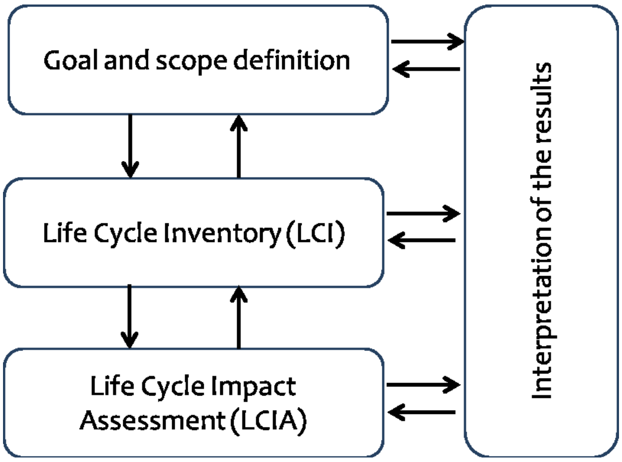

Figure 1 – LCA framework according to ISO

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 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 abovementioned assumptions are reported for transparency in this first step to avoid any misunderstanding of the LCA results and to improve the possibility of comparison.

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. LCA is widely used today, 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, the iteration of the LCA will be enlisted 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 documents to achieve the aim of task 8.2 is EPD PCR 2019:10 VERSION 2.0. The document constitutes Product Category Rules (PCR) for prepared and preserved vegetable and fruit products, including juice, developed in the framework of the International EPD System: a program for type III environmental declarations according to ISO 14025:2006. Although not specific for sea fennel, the document gives many indications on how to perform an LCA on a vegetable preserve and has been considered as a reference. The document is also connected to EPD PCR 2020:07, used for task 8.1.

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

- Functional Unit: 1 kg of packaged new sea fennel food product (the weight of packaging not included in this 1 kg)
- System boundary: from cradle to the processing gate.
- 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 are considered in the LCA of fresh sea fennel preserves:

- Sea fennel cultivation from task 8.1
- Transportation from the field to the processing site
- Manufacturing of primary and secondary packaging, if applicable
- Transportation of inputs and materials (especially primary packaging) to the processing site
- Production of ingredients, preservatives, emulsifiers, and additives used in the product,
- Production of auxiliary products used such as detergents for cleaning, refrigerating, etc.
- Production of primary, secondary, and tertiary packaging materials
- Amounts of inputs of energy (fuels, electricity) and materials (ingredients, preservatives, emulsifiers, additives) used for sea fennel preserves
- Cold chain operations
- Direct emissions from sea fennel processing
- Waste treatment of waste generated during processing and end-of-life packaging

Primary data have been collected from P3, and secondary data taken from LCA databases (Ecoinvent, Agrifootprint, Agribalyse, World Food LCA database, etc.) and scientific literature.

The impact assessment has been carried out to evaluate the most important impact indicators (e.g., global warming potential, acidification potential, eutrophication potential, abiotic depletion potential) using a specific LCA software equipped with updated LCA databases.

1.3 Data and System Description

Goal and scope definition

The goal of the study was to evaluate the environmental performance of two novel sea fennel-based products (fermented pickled sea fennel and dried sea fennel spice). This study sought to identify key environmental hotspots within the production and processing chains of these products. This information will be crucial to food manufacturers to guide the development of more sustainable production practices and inform the eco-design of these products prior to their full-scale commercialization.

Foreground data were sourced from the Rinci S.r.l. Company located in Castelfidardo, Marche region, and supplemented with background data from the Ecoinvent v.3.9.1 database (allocation, cut-off by classification processes), the World Food LCA Database, and the AGRIBALYSE database. The processing data correspond to the year 2024.

The LCA adopted a cradle-to-grave approach for both products, excluding the retail and use phases. This includes upstream processes such as sea fennel cultivation, core processes such as transportation, processing, and packaging, and downstream processes such as primary packaging end of life. The general system boundary for both products is shown in Fig. 2, while detailed system boundaries for the spice and pickles are demonstrated in Fig. 3A and 3B, respectively. Regarding the fermented pickled sea fennel, two methods for producing the product were analyzed:

- Salt stabilization and cold storage.
- Pasteurization for room temperature storage.

Retail and consumer use phases were excluded from the primary analysis due to the limited data availability for these stages as the products are not yet commercially available. However, the potential environmental impacts of these phases were considered in a sensitivity analysis. Figures 1A and 1B visually represent the system boundaries for each product.

The company manufactures and packages both products on-site, except for sea fennel milling for spice production. The functional unit representing the system for each product was defined as:

- 1 bottle of sea fennel spice (30 g, excluding packaging weight), and
- 1 jar of sea fennel pickles (100 g of fermented sea fennel and 100 g of brine solution, excluding packaging weight).

Inventory data were normalized based on these functional units to conduct the impact assessment.

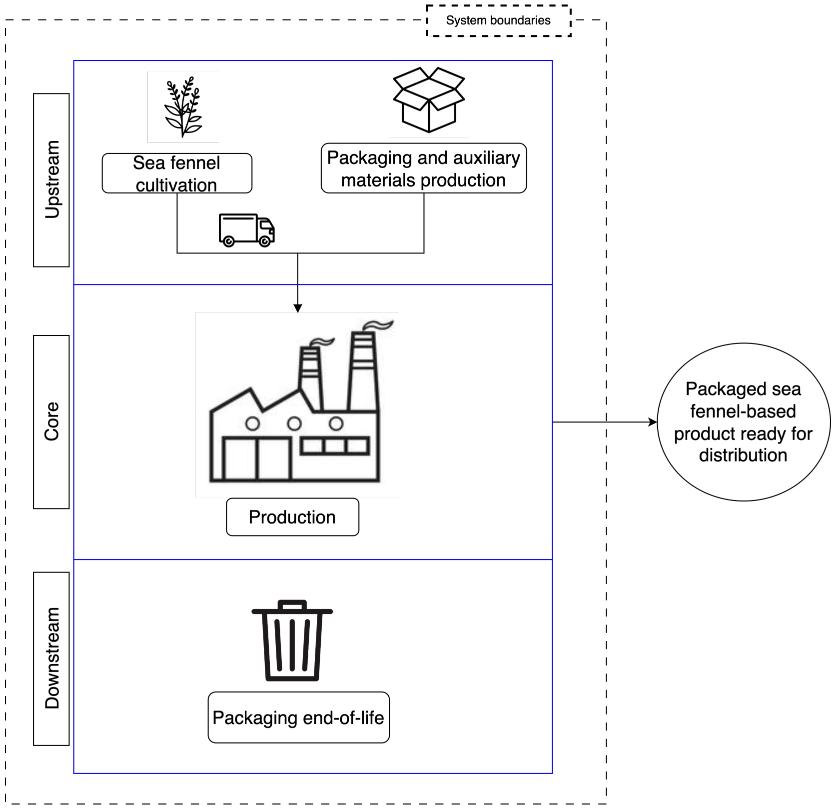

Fig. 2. The system boundary considered for the new sea fennel-based products.

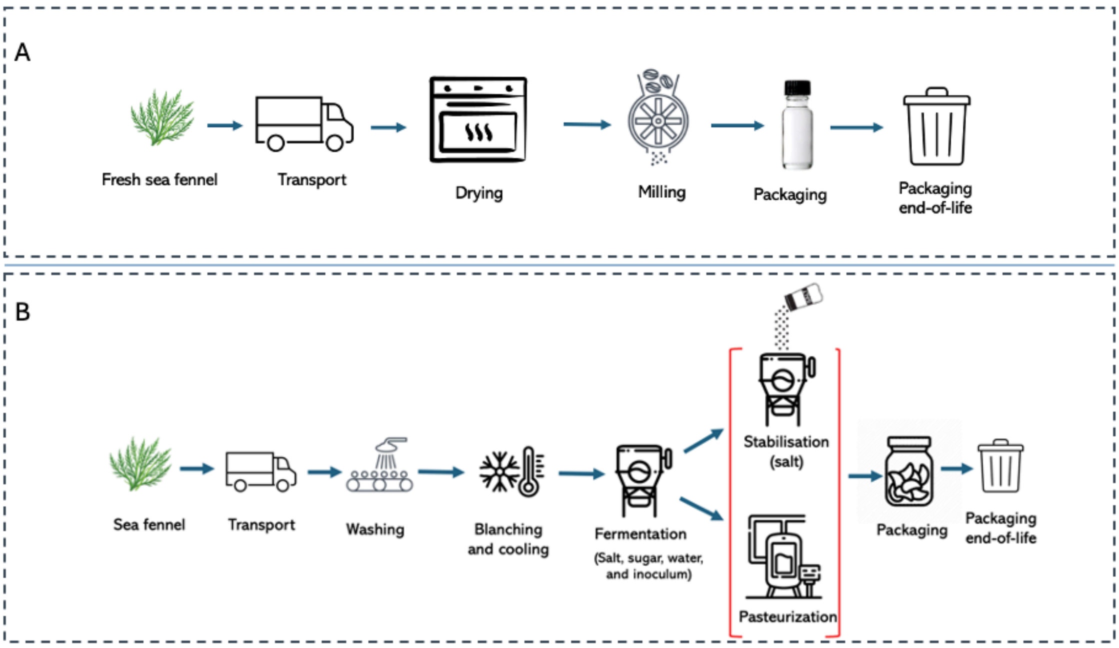

Fig. 3. System boundaries and production stages for sea fennel spice (A) and fermented pickled sea fennel (B).

System description

The upstream process of sea fennel cultivation was previously assessed in task 8.1 by Duca et al. (Duca et al., 2021). The sea fennel was cultivated in open fields using standard agricultural practices in Camerano, in the Marche region of Italy.

Sea fennel spice

To produce sea fennel spice, fresh sea fennel biomass is harvested and transported to the processing facility in plastic crates made of high-density polyethylene (HDPE) using a 7.5 - 16 t, Euro 5 truck. The transportation distance is approximately 20 km. At the processing facility, the fresh biomass (3000 kg) is placed in stainless-steel containers within a large drying chamber. The drying process takes 5 – 7 days at 40 °C, which is longer than typical spices due to the succulent nature of the leaves and the thickness of the membranes, which slow transpiration. The dryer operates on methane and includes a 10 kW fan for air circulation, controlled by adjustable flaps. The dried biomass is then transported within 10 km to an external facility for milling. A hammer mill (250 kW) with a capacity of 8 h/t is assumed for this stage. The milled spice is returned to the processing facility for packaging. Each unit consists of a 10 cL glass jar containing 30 g of dried sea fennel (12% moisture content), sealed with low-density polyethylene (LDPE) film, and equipped with a perforated polypropylene dispenser cap. Figure 1A provides a schematic overview of the sea fennel spice production process, while Table 1 presents the inventory data based on the FU (30 g of sea fennel spice in a glass bottle).

Table 1. Inventory data for spice production per functional unit.

Input	Unit	Value
Fresh sea fennel biomass	g	164
Transport	kgkm	3.28
Plastic crates	kg	1.77×10^{-4}
Natural gas	MJ	0.48
Electricity	kWh	0.152
Polypropylene bags	kg	1.77×10^{-4}
Glass container (10 cL vol)	g	115
Perforated plastic cover (polypropylene)	g	5.2
Plastic film (secondary packaging)	g	0.325

Sea fennel pickles

To produce pickled sea fennel, the same transport conditions for the spice production were applied. The pickle production involved two slightly different process flows, resulting in two different products: fermented sea fennel (pasteurized) and fermented sea fennel (brine-preserved).

The brine-preserved sea fennel pickle production begins with several pretreatment steps, including washing, blanching in water at 90°C, and subsequent cooling. Washing is conducted in a stainless-steel container where 25 kg of sea fennel is processed per cycle using 150 L of water. Blanching and cooling occur in the same container, divided into two sections. Each cycle processes 25 kg of sea fennel with 150 L of water, which is reused for up to 10 cycles. Cooling requires an additional 150 L of water per cycle. At room temperature, the fermentation phase is carried out in a 220 L stainless steel drum. Each batch processes 50 kg of fresh sea fennel with 10.5 kg of salt, 1.5 kg of sugar, 150 L of water, and a lactic acid bacteria inoculum. Fermentation occurs at room temperature for 1 – 2 months, allowing for the development of desired flavour and acidity profiles. Following fermentation, the product undergoes stabilization by increasing the salt concentration in the brine from 5% to 8%, requiring an additional 4.5 kg of salt per 150 L of solution per cycle.

The second production scenario for fermented sea fennel pickle involves pasteurization to enable room temperature storage. Following fermentation, the sea fennel is removed from the brine solution and washed with 225 kg of water to reduce the salt concentration from 5% to 2%. Subsequently, the fermented sea fennel undergoes pasteurization. Based on data from Djekic et al. (2014), we assumed an energy consumption of 0.09 kWh and a water consumption of 2.46 L/kg of sea fennel for the pasteurization process. Following pasteurization, the product is cooled using an equal volume of water.

The final product is packaged in glass jars (189 g) with tin-plated steel lids (15 g), each containing 100 g of fermented sea fennel and 100 g of brine. Table 2 provides the inventory data for the two production scenarios, based on a functional unit of 1 jar of pickled sea fennel.

Table 2. Inventory data for pickled sea fennel production per functional unit (100 g of fermented sea fennel and 100 g of brine in a glass jar).

Input	Unit	Pickled sea fennel (pasteurized)	Pickled sea fennel (brine preserved)
Fresh sea fennel biomass	g	105	105
Transport	kgkm	2.1	2.1
Plastic crates	kg	1.14×10^{-4}	1.14×10^{-4}
Water	L	2.05	1.56
Energy	kWh	9.41×10^{-3}	2.68×10^{-4}
Salt (NaCl)	g	21	30
Sugar (fructose)	g	3	3
Microbial starter (LAB)	g	0.02	0.03
Glass jar	g	189	189
Metal lid (tinplated)	g	15	15

Primary packaging end-of-life

Recognizing the potential environmental impact of packaging waste for food products, the LCA included the end-of-life phase for all primary packaging materials used in producing and distributing the two sea fennel-based products. For this phase, the impact relating to the end of life of the packaging was estimated, i.e., the glass (bottle for spice and jar for pickle), tin-plated metal lid (pickle), and plastic cap (spice). The environmental impacts of packaging waste were assessed based on typical Italian waste management scenarios. The following assumptions were made regarding packaging end-of-life:

- Glass: 81% recycling, 19% landfilling
- Plastic: 63% incineration, 31% recycling, 6% landfilling

- Tin-plated steel: 81% recycling, 19% landfilling

These assumptions reflect the current recycling rates for these materials in Italy (COREPLA, 2022; CoReVe, 2022; Ricrea, 2022).

Life cycle impact assessment

We evaluated the impact assessment of new sea fennel-based product, per the selected functional units, in terms of acidification (A), climate change (CC) estimated over a 100-year horizon, ecotoxicity freshwater (ETF), particulate matter (PM), eutrophication marine (MEU), eutrophication freshwater (FEU), eutrophication terrestrial (TEU), human toxicity, cancer (HTC), human toxicity, non-carcinogenic (HTNC), ionizing radiation (IR), land use (LU), ozone depletion (OD), photochemical ozone formation (POF), water use (WU), resource use, fossils (FRD), and resource use, minerals and metals (MRD), using the Environmental Footprint (EF) 3.1 midpoint life cycle impact assessment (LCIA) method.

Interpretation

The interpretation of the LCA results encompasses midpoint impact scores based on the EF 3.1 method, a contribution analysis to identify key impact areas, and sensitivity analyses to assess the influence of different scenarios.

1.4 Main findings

Environmental impacts of sea fennel spice

The impact scores for the different impact categories based on the EF 3.1 method for sea fennel spice are provided in Table 3. The midpoint score for CC impact was determined to be 0.19 kg CO_2 eq./FU. Fig. 3 presents a hotspot analysis of sea fennel spice production, illustrating the contributions of various processes to the overall environmental impact across multiple categories. The contributions of each process varied depending on the impact category. However, primary packaging and energy consumption were the main contributors.

Table 3. Midpoint impact scores for sea fennel spice, expressed per FU.

Impact category	Unit	Value
A	mol H^+ eq.	9.31×10^{-4}
CC	kg CO_2 eq.	0.188
ETF	CTUe	0.496
PM	disease inc.	7.08×10^{-9}
MEU	kg N eq.	1.79×10^{-4}
FEU	kg P eq.	3.25×10^{-5}
TEU	mol N eq.	1.94×10^{-3}
HTC	CTUh	5.78×10^{-11}
HTNC	CTUh	1.48×10^{-9}
IR	kBq U-235 eq.	1.67×10^{-2}
LU	Pt	17.96
OD	kg CFC11 eq.	3.60×10^{-9}

POF	kg NMVOC eq.	6.56 x 10^{-4}
FRD	MJ	2.574483
MRD	kg Sb eq.	9.00 x 10^{-7}
WU	m^3 depriv.	4.94 x 10^{-2}

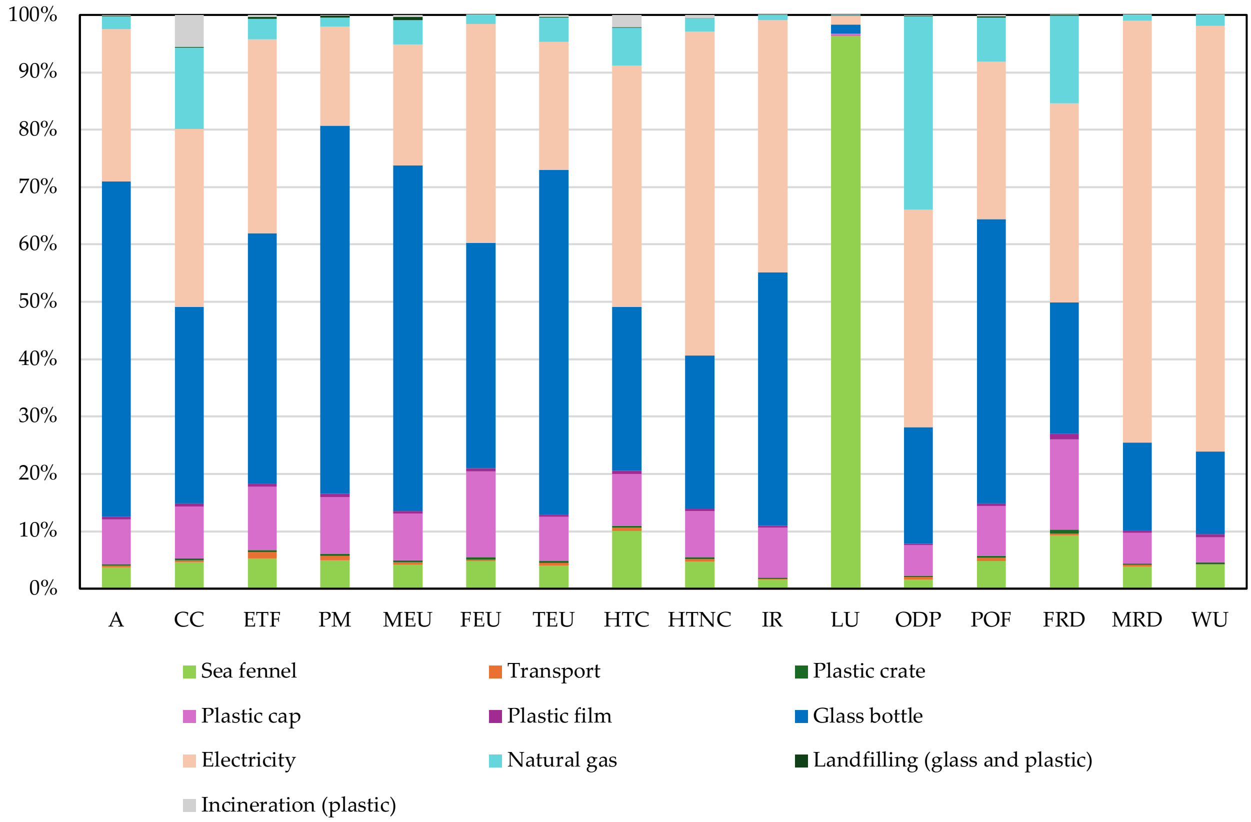

Fig. 3. Contribution analysis of sea fennel spice (30 g in a glass bottle with a plastic cap).

The primary packaging, consisting of a glass bottle and plastic cap, significantly contributed to all the impact categories except LU, WU, MRD, and ODP where it accounted for less than 50%. Among the primary packaging materials, glass was the main contributor, accounting for 50 – 60% of the total impacts of A, PM, MEU, TEU, and POF. The plastic cap contributed less than 12% to all the impact categories, except for FRD and FEU, where it accounts for 16% and 15%, respectively of the total impacts. This significant contribution is predominantly driven by impacts related to glass production and the considerable amount of glass used. Each glass container weighs 115 g, nearly four times the product's weight (30 g of spice per unit).

To mitigate the environmental impact of packaging, several strategies can be considered, including improving glass recycling rates, considering that glass can be reused and fully recycled. Additionally, reusing glass containers or implementing returnable glass container systems, particularly for local and regional markets, can minimize the need for new glass production. Investigating the use of lighter-weight and more sustainable packaging materials with comparable barrier properties could also be explored. Similarly, improving plastic waste management is crucial for plastic packaging to mitigate its environmental impact. Efforts to enhance plastic waste management, promote recycling, and develop alternative, more sustainable packaging materials are essential to address the environmental challenges associated with plastic use.

Energy consumption emerged as a significant contributor to several environmental impact categories, with electricity contributing substantially to impacts related to IR (44%), HTNC (56%), MRD 73%, and WU 73%. Natural gas consumption significantly contributed to ODP (34%) and FRD (15%). Due to its high water content, the extended drying time required for sea fennel biomass contributes significantly to the overall energy demand. Therefore, transitioning to renewable energy sources for the drying process could be crucial for improving the environmental performance of these products. Other minor contributing factors included sea fennel biomass, material use, transportation, and waste management. However, LU impacts were primarily associated with sea fennel cultivation although low in absolute value. A previous study by Duca et al. (2024) demonstrated the relatively low environmental impact of sea fennel cultivation due to the low input requirements. Transportation impacts were also negligible due to the proximity of the cultivation site to the processing facility.

Sensitivity analysis for sea fennel spice

Primary packaging option

Table 4 presents the results of the scenario analysis conducted to evaluate the environmental impacts of different packaging options for sea fennel spice. The baseline scenario consists of a glass jar with a plastic cap. This baseline scenario was compared with two alternative scenarios: Scenario 1, substitution of the glass container with an HDPE plastic bottle, and Scenario 2, refilling of the original glass jar with spice delivered in an LDPE plastic sachet.

Replacing the glass container with an HDPE bottle leads to mixed environmental outcomes. Improvements are observed in impact categories such as A, EFT, PM, MEU, TEU, IR, and POF. These reductions can be attributed to less amount of HDPE material used compared to glass. However, it resulted in significant increases in OD and MRD. The increased OD impact may result from the chemicals and processes involved in HDPE production, while MRD is negatively impacted due to the extraction and processing of petroleum-based feedstocks for plastic manufacturing. Other categories, including CC, FEU, LU, and FRD, exhibit negligible changes. Scenario 2 demonstrated the most significant environmental improvements, with negative values observed across all impact categories, indicating an overall reduction in environmental impact compared to the baseline scenario. This scenario resulted in an average impact reduction of 44%. The reductions are primarily due to the much lighter weight of LDPE sachets compared to glass or HDPE containers, which significantly reduces raw material use, transportation emissions, and energy consumption during production. By reusing the glass container multiple times, this scenario minimizes waste generation and reduces the environmental burden associated with primary packaging production and disposal.

The findings emphasize the critical role of packaging materials in determining the overall environmental performance of sea fennel spice products. While substituting glass with HDPE bottles (Scenario 1) offers partial benefits, it introduces significant drawbacks in other categories like OD and MRD, potentially offsetting the gains. On the other hand, adopting a refill system (Scenario 2) with LDPE sachets addresses these shortcomings and maximizes resource efficiency and waste reduction. Implementing Scenario 2 would require consumer buy-in, involving behaviour changes, such as refilling and maintaining glass containers. Additionally, careful design of the LDPE sachets is necessary to ensure they remain lightweight while maintaining durability and product protection. Improving glass recycling rates could complement this strategy, further reducing environmental impacts. This analysis highlights the potential of circular economy principles, such as reuse and waste minimization, to drive sustainability in packaging systems.

Table 4. Relative changes of different packaging scenarios for sea fennel spice relative to the baseline scenario.

Impact category	Scenario 1	Scenario 2
A	-39%	-65%
CC	-3%	-47%
ETF	-16%	-54%
PM	-39%	-72%
MEU	-39%	-67%
FEU	-2%	-52%
TEU	-40%	-66%
HTC	6%	-38%
HTNC	11%	-34%
IR	-20%	-51%
LU	0%	-2%
OD	4110%	-25%
POF	-29%	-57%
FRD	5%	-38%
MRD	390%	-20%
WU	10%	-18%

Baseline scenario – glass bottle with plastic cap, Scenario 1 – plastic bottle with plastic cap, and Scenario 2 – refilling of glass bottle with plastic cap with sea fennel spice in sachet.

Alternative energy source

The substitution of grid electricity with electricity generated from a 3 kWp building-integrated photovoltaic (PV) system resulted in a modest average impact reduction of 11%. This scenario demonstrated the greatest improvements in WU (32%) and IR (23%), as shown in Fig. 4. However, it also led to an 8% increase in MRD due to the upstream environmental burden of PV technology, which requires high-purity materials and energy-intensive production processes. While solar energy offers potential environmental benefits, several challenges must be addressed for its effective implementation. First, the upfront costs of installing a PV system can be a significant barrier for small- to medium-sized enterprises (Qamar et al., 2022), particularly those involved in niche agricultural products like sea fennel spice. Although long-term energy cost savings can offset these costs, the initial investment may deter adoption without government subsidies or financial incentives. Secondly, seasonal variability in solar energy generation poses a significant challenge. This could necessitate supplementary energy from the grid during periods of low solar output (Ahmed et al., 2020), slightly diminishing the overall environmental benefits. Additionally, the disposal and recycling of end-of-life PV panels pose a significant environmental challenge. Current recycling technologies are still under development, and the potential for material recovery and reuse remains limited (Lunardi et al., 2018; Mao et al., 2024). Despite these challenges, integrating PV systems into the production of sea fennel spice offers a promising pathway toward greater sustainability.

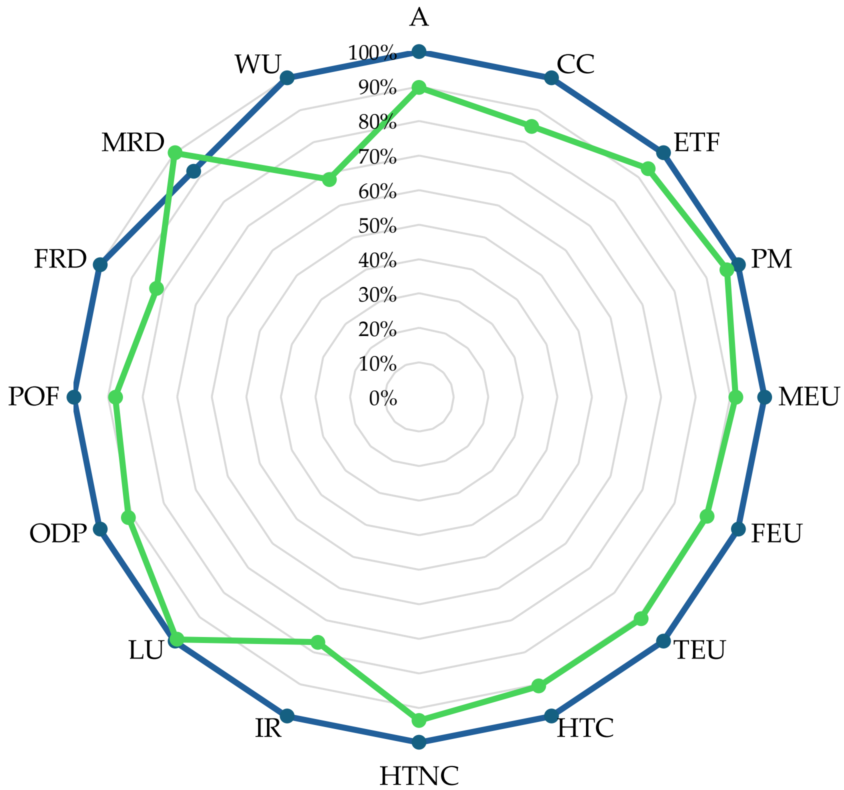

Fig. 4. Scenario analysis of energy consumption: comparison of baseline scenario (grid electricity) and alternative scenario (photovoltaic electricity). Blue line (baseline scenario); green line (alternative scenario).

Environmental impacts of pickled sea fennel

Table 2 presents the midpoint impact results for both pasteurized and brine-preserved pickled sea fennel. Overall, both production scenarios showed similar environmental impacts across most impact categories. However, WU was significantly higher (36%) for the pasteurized product due to the additional water consumption during the pasteurization process. CC impact was similar for both scenarios, with a midpoint score of 0.18 kg CO_2 eq./FU. As illustrated in Figure 1B, the primary distinction between the system boundaries of the two products lies in the stabilization method. In the pasteurized product, the pasteurization step replaces the salt stabilization process used for the brine-preserved product. However, the interchangeable stabilization steps are not significant contributors to the overall environmental impact. As a result, the scores for most impact categories remain largely consistent between the two products. This analysis highlights that, aside from the increased water use in pasteurization, the environmental performance of the two methods is comparable.

Table 5. Midpoint impact scores for pickled sea fennel, expressed per 1 jar of product (100 g sea fennel and 100 g brine).

Impact category	Unit	Pickled sea fennel (pasteurized)	Pickled sea fennel (brine preserved)
A	mol H^+ eq.	1.25×10^{-3}	1.25×10^{-3}
CC	kg CO_2 eq.	0.179	0.178
ETF	CTUe	0.992	1.006
PM	disease inc.	1.23×10^{-8}	1.23×10^{-8}
MEU	kg N eq.	2.84×10^{-4}	2.85×10^{-4}
FEU	kg P eq.	5.29×10^{-5}	5.32×10^{-5}
TEU	mol N eq.	3.01×10^{-3}	3.02×10^{-3}
HTC	CTUh	1.72×10^{-10}	1.72×10^{-10}
HTNC	CTUh	1.89×10^{-9}	1.90×10^{-9}
IR	kBq U-235 eq.	1.38×10^{-2}	1.35×10^{-2}
LU	Pt	12.25	12.25
OD	kg CFC11 eq.	1.41×10^{-9}	1.34×10^{-9}
POF	kg NMVOC eq.	8.21×10^{-4}	8.19×10^{-4}
FRD	MJ	1.86	1.83
MRD	kg Sb eq.	1.19×10^{-5}	1.19×10^{-5}
WU	m^3 depriv.	0.13	0.09

Fig. 5 and 6 present the relative contribution analysis of the environmental impacts of pasteurized and brine-preserved pickled sea fennel, respectively. Across both production scenarios, primary packaging emerged as the dominant contributor to most impact categories, accounting for over 80% of the total impact in most cases except for ODP (61%), WU (19%), and LU (7%). Among the primary packaging components, glass was identified as the dominant contributor to environmental impacts. On average, glass accounted for 47% of the total impact and exceeded 70% in specific categories such as A, CC, PM, MEU, TEU, and POF. Using glass as packaging material for pickles is common. Glass is a widely used and preferred packaging material for food products, especially for pasteurized products, due to its heat resistance, chemical inertness, impermeability, durability and strength under pressure, transparency, consumer perception of premium quality and safety, and ease of cleaning, reuse, and recycling. However, glass packaging has a significant environmental footprint, primarily due to the energy-intensive processes involved in its production and transportation (Gazulla et al., 2010). To mitigate the environmental impact of packaging, several strategies, such as reducing glass weight, exploring alternative packaging materials that can deliver the same function, and improving glass recycling rates, can be considered to improve the sustainable production of pickled sea fennel. The tin-plated chromium steel lid emerged as the second most impactful input in the production of pickled sea fennel, contributing an average of 30% to the overall environmental impact. Its most significant contributions were observed in specific categories, including MRD (94%), HTC (64%), ODP (44%), FEU (41%), and HTNC (41%). While aluminium could be considered an alternative to steel for lids, its suitability is limited for pasteurized products due to potential instability during high-temperature processes (Gül et al., 2022). However, aluminium lids could be a viable option for brine-preserved pickled sea fennel, where pasteurization is not required.

Beyond the primary packaging, several other materials and processes contributed to the environmental impacts. Sea fennel biomass contributed significantly (91%) to LU impact due to the land area required for cultivation, although very low in absolute terms. Water consumption during various processing stages, including washing, blanching, cooling, and fermentation, significantly impacted WU. Fructose contributed 27% to ODP due to the environmental impacts associated with its production, including agricultural practices, industrial processing, and energy consumption (Chauhan et al., 2011). Energy consumption, transportation, and other inputs generally had minor contributions to the overall environmental impact.

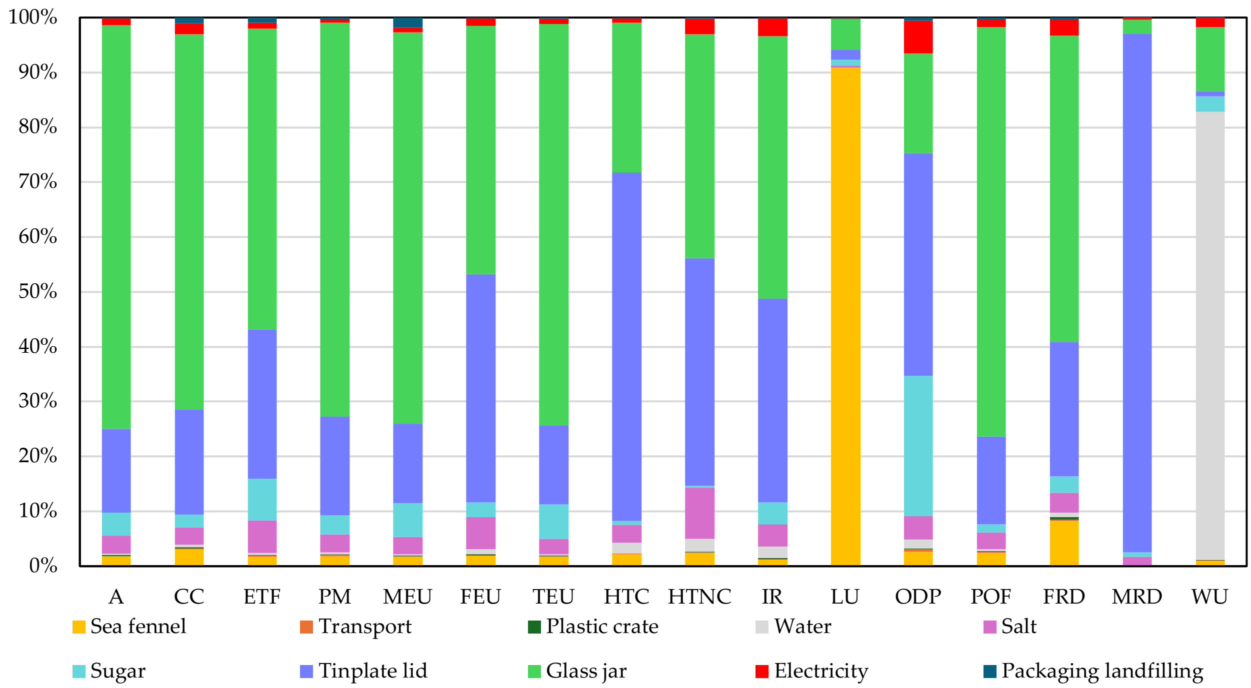

Fig. 5. Contribution analysis of pasteurized pickled sea fennel in a glass jar.

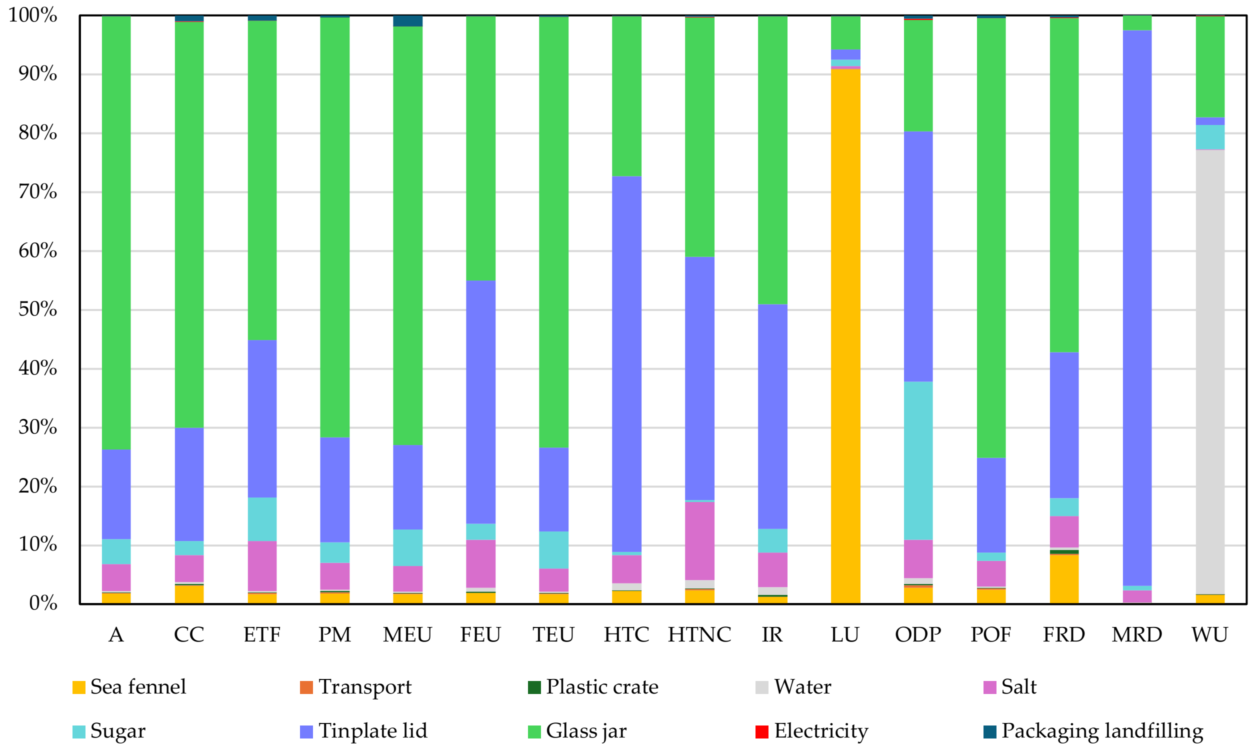

Fig. 6. Contribution analysis of brine-preserved pickled sea fennel in a glass jar.

Sensitivity analysis for pickled sea fennel

Lid Material Comparison

For the brine-preserved pickled sea fennel, substituting the tin-plated chromium steel lid with an aluminium lid resulted in slightly improved environmental performance across all impact categories, with an average reduction of 11%. This improvement was most pronounced for HTC (48%), IR (31%), ODP (24%), and WU (36%), as shown in Fig. 7. However, aluminium lids are unsuitable for pasteurized products due to their lower thermal stability, which can lead to lid deformation and potential product spoilage during the pasteurization process. The environmental benefits of the aluminium lid primarily stem from its lower density than steel, leading to reduced material use and associated environmental impacts. However, the actual weight of the aluminium lid may vary depending on its thickness and design. To further optimize the environmental performance of the lids, careful design considerations are crucial. Minimizing the weight of the lids while maintaining their functionality and ensuring product safety is essential to reduce their environmental impact.

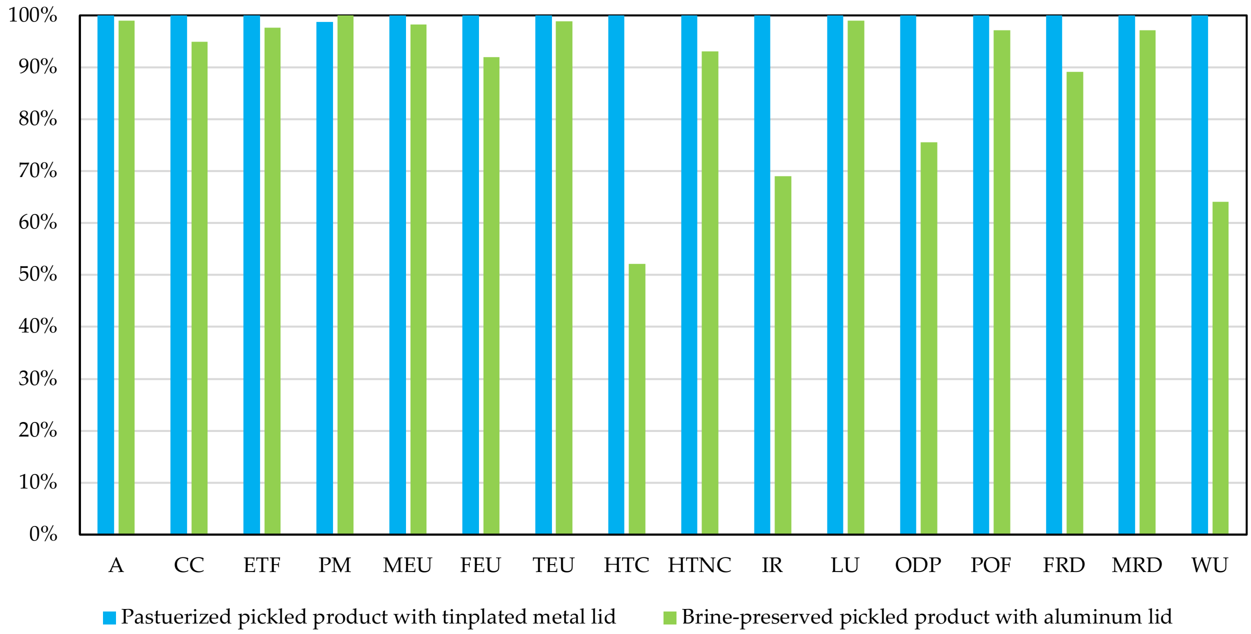

Fig. 7. Environmental impact comparison: Influence of lid material (steel vs. aluminium) on pickled sea fennel production.

3.4.2 Shelf life (storage conditions)

As shown in Fig. 8, the analysis reveals that the pasteurized product had lower environmental impacts across all impact categories, except WU, with an average reduction of 24% compared to the brine-preserved product. Significant reductions were observed in ODP (89%), IR (62%), and FEU (41%). Given the minor differences in environmental impacts during the production phase, the observed variations primarily stem from the distinct storage and distribution requirements of each product. Brine-preserved requires continuous refrigeration throughout its shelf life, leading to higher energy consumption for cold chain maintenance during transportation and storage. Pasteurized allows for room temperature storage before opening, reducing the need for continuous refrigeration and associated energy consumption. Therefore, pasteurized pickled sea fennel offers potential advantages, particularly for extended storage times. Another critical advantage of pasteurized pickled sea fennel is its suitability for long-distance transport and export. This characteristic also translates into potential cost savings, as cold storage and refrigerated transportation incur substantial energy costs.

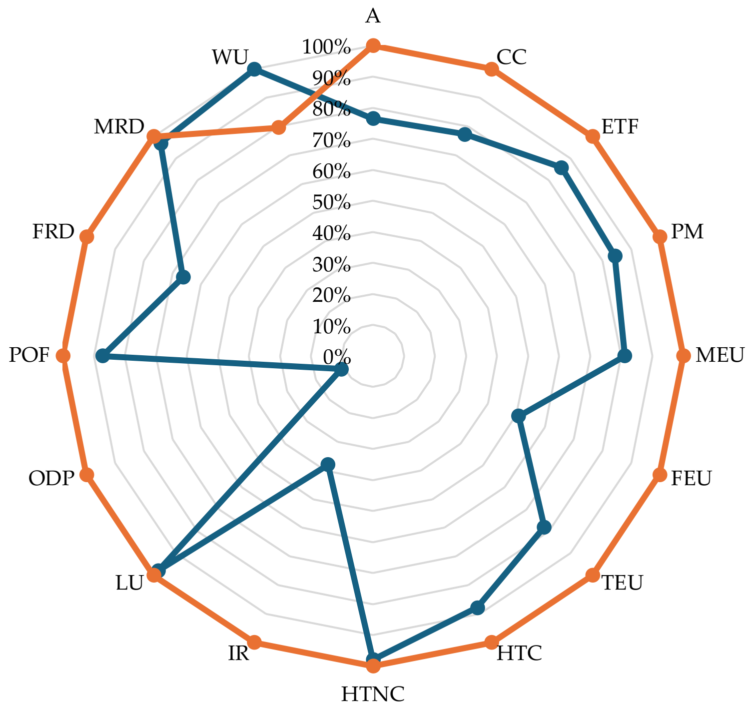

Fig. 8. Relative environmental impacts of pasteurized (Scenario 1) and brine-preserved (Scenario 2) pickled sea fennel, including the retail and use phases. Scenario 1 includes six months of shelf life followed by 7 days of refrigeration after opening. Scenario 2 assumes six months of refrigerated storage. Blue line: Scenario 1; Orange line: Scenario 2.

1.5 Conclusions

This study assessed the environmental performance of two innovative sea fennel-based products (sea fennel spice and fermented pickle) at the product development stage, contributing to the eco-design of sustainable food products.

The results demonstrated that primary packaging, particularly the use of glass, was the dominant contributor to environmental impacts across most categories for both products. While glass packaging offers advantages such as chemical inertness, transparency, and recyclability, its significant weight and energy-intensive production process underscore the need for alternative solutions. Scenarios exploring the substitution of glass containers with HDPE bottles and the use of refillable glass containers with spice delivered in lightweight plastic sachets revealed substantial potential for environmental improvements, particularly in the latter scenario, which showed an average impact reduction of 44%. For energy use, transitioning from grid electricity to solar energy through a PV system resulted in a marginal average impact reduction of 11% for spice production. However, the increased material resource depletion associated with PV panel production highlights the trade-offs in adopting renewable energy systems.

In the case of fermented pickles, the comparison between pasteurized and brine-preserved products indicated that pasteurization has distinct advantages in reducing environmental impacts during the retail and use phases. Eliminating the need for continuous refrigeration in pasteurized products reduces energy consumption and improves long-distance transport and export feasibility. While pasteurization offers these advantages, it is important to acknowledge that the process increases water consumption. Therefore, optimizing water efficiency within the pasteurization process is crucial for minimizing environmental impact. Regarding packaging, substituting the tin-plated chromium steel lid with an aluminium lid in the brine-preserved product resulted in a slight improvement in environmental performance across all impact categories. This highlights the importance of careful design considerations for lids, emphasizing the need to minimize their weight while maintaining their functionality, durability, and ability to ensure product safety, as this offers a viable pathway for more sustainable packaging solutions.

A key limitation of this study is the reliance on pilot-scale data, which may not fully capture the environmental performance at commercial production scales but this aspect is common for eco-design. Additionally, exclusions such as transportation impacts for some materials and packaging components could lead to underestimating total impacts. Future research should address these gaps by incorporating full-scale production data and a more comprehensive supply chain analysis.

Overall, this study provides a foundation for understanding the environmental impacts of vegetable preserves and offers actionable recommendations for improving their sustainability. By addressing the identified hotspots, such as packaging and energy use, while considering the trade-offs of alternative materials and processes, the eco-design of these novel products can align with broader sustainability goals in the food industry.

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Costantini, E.; Boakye-Yiadom, K.A.; Ilari, A.; Foppa Pedretti, E.; Duca, D. Environmental Impact Assessment of New Sea Fennel-Based Food Products: Spice and Fermented Pickles. Sustainability 2025, 17, 1869. https://doi.org/10.3390/su17051869

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