DEPARTMENT OF AGRICULTURAL, FOOD AND ENVIRONMENTAL SCIENCES
DEGREE COURSE: FOOD AND BEVERAGE INNOVATION AND MANAGEMENT

SUSTAINABILITY ASSESSMENT OF NEW SEA FENNEL-BASED PRODUCTS

TYPE OF DISSERTATION: (research)

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ACADEMIC YEAR 2023/2024

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INTRODUCTION AND AIM OF THE THESIS

Sea fennel (Crithmum maritimum L.) is a perennial halophyte recognised for its ability to thrive in saline and nutrient-poor environments, making it a promising crop for sustainable agriculture. Sea fennel has a rich history of use that spans culinary and medicinal application, particularly in coastal regions of Europe and the Mediterranean. Its leaves and stems are rich in celery-like flavour with salty, citrusy notes followed by a pungent aftertaste rendering it a versatile ingredient for salads, soups and sauces. It has been largely used in traditional preparation consumed as fresh, boiled to soften its texture, or preserved in olive oil or brine. Sea fennel preserved in vinegar was used from sailors during long trip to protect against scurvy. In the folk medicine tradition, sea fennel was used as diuretic, carminative and tonic. Sea fennel is used in feed formulation of rabbits as supplement. It is a rich source of many health-promoting compounds such as polyphenols, carotenoids, minerals and antimicrobial compound.

After a period in which the plant disappeared from some natural environments due to indiscriminate harvesting, sea fennel is now attracting interest as an ingredient for innovative food products and as a source of bioactive compounds for nutraceutical and pharmaceutical applications. Another strong point is the cultivation of sea fennel: being halophyte, this plant has very low water requirement and no fertilisation needed. It is adapted to nutrient-poor environments. Moreover, the production of secondary metabolites which confer the health-promoting benefits to the plant, are produced mainly under stress condition.

The use of this resource entails the formulation of new sea fennel-base products as studied for example in the project “Sea Fennel for Med”. Beyond the economical aspect and the potential applications, it is important to consider the environmental impacts of new sea fennel-based products.

This study investigates the environmental impact of three new sea fennel-based products not yet present on the market, represented by sea fennel spice, pasteurized fermented sea fennel and fresh fermented sea fennel, by Life Cycle Assessment (LCA), a widely recognized framework that adhere to ISO Standard 14040 and 14044. The results of LCA analysis allow in determining the overall environmental footprint, identify hotspots and explore opportunities for improvement. This environmental information can help to drive the design of new products.

CHAPTER 1
DESCRIPTION OF SEA FENNEL

1.1 **Taxonomy and morphological feature of *Crithmum maritimum***

Sea fennel (*Crithmum maritimum L.*) is a perennial facultative halophyte herb species, meaning that it can tolerate and survive in saline environments, as few species can do, such as soils impregnated with seawater or regularly exposed to the splashing of sea waves. *C. maritimum* grows spontaneously on cliffs along rocky or sandy coasts especially along the coastal area of Southern and Western European countries of the Mediterranean Sea, North America, Central and Western Asia (Kraouia et al., 2023).

Figure 1-1 Rock samphire in natural environment with inflorescence.
(Inventaire National Du Patrimoine Naturel INPN, 2024).

The indiscriminate harvesting of sea fennel during the years has led to the disappearance of this plant from some natural environment. For this reason, in some region, such as England and Mt. Conero Natural Park of Marche Region in Central Italy, the plant in now protected and its harvest from the wild is forbidden (Kraouia et al., 2023; Nartea et al., 2023). During the last years, an increasing number of small and medium enterprises in the Mediterranean basin have started to cultivate this crop, which is recently claimed “cash crop” or “emerging crop”, for the high potential in adaptation (Nartea et al., 2023). Nowadays, in a period where we are faced with water scarcity, soil salinization due to climate change, erosion and intensive agriculture, the interest in halophytic plants, which represent only 1% of all plants, is growing. Among these, sea fennel would represent an opportunity for saline agriculture thanks to its adaptation mechanism against stressful environmental conditions such as drought, high temperatures, nutrient limitations and high salinity (Generalić Mekinić et al., 2024).

Regarding the taxonomy of *C. maritimum, it* belongs to the genus *Crithmum* and to the *Apiaceae* family, the same family of parsley and celery. The term *Crithmum* derived from Greek krithe (barley), due to the resemblance of fruits to barleycorns; *maritimum* because of the sea environment, where it grows. Sea fennel is also known as *kritmo* in Greece, *Saint Peter’s herb* in England (referred to the patron saint of fishermen), *criste marine* in France, finocchio marino in Italy and specifically ‘paccasassi’ in the Monte Conero area, South of Ancona, where this plant spontaneously grows (Kraouia et al., 2023; Piatti et al., 2023; Renna et al., 2017). More details about the taxonomy are given in the Fig.1-2.

Taxonomy

Kingdom:	Plantae
Subkingdom:	Tracheobionta
Superdivision:	Spermatophyta
Division:	Magnoliophyta
Class	Magnoliopsida
Subclass:	Rosidae
Order:	Apiales
Family:	Apiaceae
Genus:	Crithmum
Species:	*Crithmum maritimum* L.

Figure 1-2 Taxonomic classification of C. maritimum, *(Atia et al., 2011).*

C. maritimum is a highly branched plant of up to 30-60 cm high with a robust rhizomatous root which can stretch up to five meters, and a branched stem, which is often woody at the base. Its seedling roots are capable of ensuring a strong adhesion to rock from the beginning of their development (Strumia et al., 2020). Leaves are persistent, glabrous, succulent and have a triangular outline, bi or tri-pennate with fleshy and keeled lanceolate segments divided into three leaflets 2-5 cm long. The plant blooms between June and September, in five-petaled and pale-yellow flowers arranged in umbels, with 10-30 rays, subdivided in umbellets surrounded by bracts. The fruit begins to mature in November-December. The flowers produce ovoid-oblong achenes 5-6 mm long and 1,5-2,5 mm large, olive-green to purple, composed of two mericarps each one divided in 5 ribs (Atia et al., 2011; Kraouia et al., 2023; Renna et al., 2017).

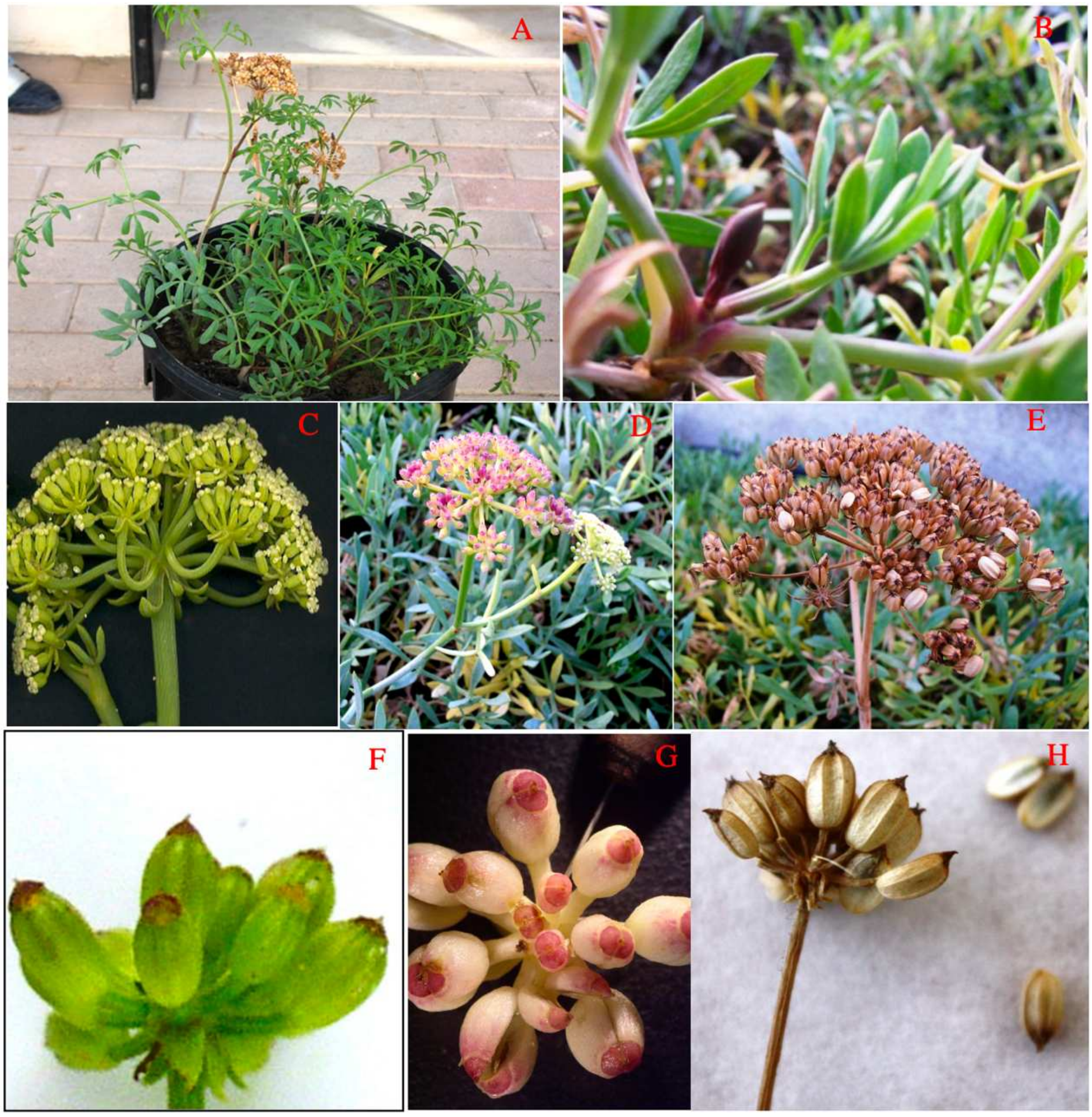

Figure 1-3 0

1.2 **Chemical composition**

Crithmum maritimum is an edible halophyte with large potential in human nutrition field. According with Martins-Noguerol et al., 2022, the nutritional composition of sea fennel presents some differences when the plant grows under field condition instead under optimal condition: the content of proteins and lipids is higher in sea fennel grown under optimal greenhouse conditions, resulting in an improved nutritional profile and sodium accumulation decreases allowing a greater consumption of this halophyte without exceeding the daily intake recommendation. Conversely, phenolics were drastically decreased likely due to the absence of stressors. The composition is reported on the following Table 1. Phenolic compounds are produced in plants by the phenylpropanoid pathway playing a role in the resistance mechanism of plants against various stress factors.

Table 1 Comparison of sea fennel nutritional profile of plant grown under field conditions and under optimal conditions.

	Protein	*Lipids*	*Sodium*	*Phenolic content*
SF field conditions	*3,8–6,2 g \100g DW*	*4,9–7,5 mg\g WW*	*3,9–5,0 g\100g DW*	*30,2-48 mg\g DW*
SF opt. conditions	*10,2 g\100g DW*	*9,6 mg\g WW*	*1,2 g\100g DW*	*6,1 mg\g DW*

Generally, plant growth can be affected by biotic stressors (fungal pathogens, bacteria, viruses, herbivores, insects, nematodes) and abiotic stressors (salinity, drought, cold, light, heat, humidity, heavy metals). Plants adopt different mechanisms to cope with environmental stressors including metabolomics, transcriptomics, proteomics and genomics. The plant metabolome consists of two kinds of metabolites: primary and secondary metabolites. Primary metabolites are essential for the proper growth and development of plants; secondary metabolites (like phenolic compounds and terpenes), have no direct role in growth, reproduction and development and are very definite in their function. Usually, they are made under particular conditions for a definite purpose, such as defence against pathogens infection, enhanced resistance to abiotic stresses and protect from UV rays, acting as antioxidant. Sea fennel is very rich in terms of health-promoting compounds, especially those with antioxidant activity like phenolic compounds which play a significant physiological role in increasing resistance and adaptableness during the life cycle of plants. Other nutritive and health-beneficial components have been detected and identified from various studies in all parts of the sea fennel: ascorbic acid, carotenoids, organic acids, fatty acids, volatiles. Also, these compounds offer a pleasant taste and health benefits, from which derives the gastronomic as well the medicinal use of *C. maritimum* (Generalić Mekinić et al., 2024; Salam et al., 2023). Sea fennel is also considered a good source of dietary fibres, proteins, minerals, vitamins C, A and E and bioactive compounds (Nartea et al., 2023).

1.3 **Gastronomic use of Sea fennel**

Sea fennel is a strongly aromatic herb with interesting sensory attributes characterized by a slightly salty taste and some notes of celery, followed from light notes of common fennel and peel of green citrus, followed by a pungency aftertaste (Politeo et al., 2023; Renna & Gonnella, 2012). It has a lot of food uses due to its aromatic traits and it has been largely used for nutritional purposes being a significant source of minerals. In many countries sea fennel leaves are traditionally used in cuisine as fresh ingredient, in salads, soups and sauces, or they are stored in vinegar like capers. This latter preparation is listed as a traditional agri-food product of Puglia by the Italian Ministry of Agriculture. According with the Marche region recipes about "Paccasassi of Conero", they are ideal served on toast in combination with salami, anchovies, mussels, smoked fish, or dairy products. Examples of dishes with sea fennel are given in the Figure 1-4 (*Rinci - Le Meraviglie Del Gusto*, n.d.).

Figure 1-4 Italian dishes with sea fennel, combined with salmon, on piadina with mortadella or served with pasta as sea fennel-pesto (Rinci - Le Meraviglie Del Gusto*, n.d.).*

The plant was consumed in the traditional diet of the first European farmers. It was cultivated in gardens and was sold on London streets as "*Crest Marine*". In British Isles, sea fennel is used in traditional recipe: the Rock Samphire Hash is prepared by mixing stems and leaves of *C. maritimum* with pickled cucumbers and capers which cooked in stock and the bound with egg yolk (Atia et al., 2011). In most Mediterranean countries, such as Greece, Cyprus, Turkey, Tunisia, Morocco, Spain, Slovenia, Croatia and Bosnia-Herzegovina, tender stems and leaves are consumed either as raw or previously boiled in water to make them softer, or preserved in olive oil, vinegar or brine. They are also consumed as appetizer with bread, olive oil and capers (Kraouia et al., 2023; Piatti et al., 2023; Renna et al., 2017). Sea fennel could be potentially used in food manufactures and cosmetology as preservative agents and biopesticides (Meot-Duros et al., 2010).

1.4 **Medicinal use of Sea fennel**

The richness of sea fennel in phenolic compounds makes this plant to be considered by both food and non-food sectors: especially secondary metabolites are distinctive means of food essence, medicines, flavourings, and other industrial material. The use of *Crithmum maritimum* in the folk medicine is reported by several authors. The plant is used as appetizer, tonic, carminative, diuretic and vermifuge. Sailors used to consume food preparation based on sea fennel or eat raw leaves to protect against scurvy. They used to bring fresh leaves with them when going on fishing trips, while on long voyages they used to keep leaves in vinegar for better preservation (Cornara et al., 2009; Cunsolo et al., 1993). The decoction of the aerial part of *Crithmum maritimum* before fructification was frequently used as a diuretic and in the treatment of kidney and urinary complaints. Corporal bath with sea fennel were also indicated to favour pregnancy. Leaf decoction was used as liver purifier and against colic. The study reports also the use of sea fennel for veterinary purposes: the aerial parts are given to rabbits as feed supplement and leaves as galactagogue (Cornara et al., 2009). Sea fennel could be used in medicine as new antibiotics. In a recent study has been showed that sea fennel apolar fraction had strong antimicrobial activity against *Micrococcus luteus, Salmonella arizonae, Erwinia carotovora, Pseudomonas fluorescens, P. aeruginosa, P. marginalis, Bacillus cereus and Candida albicans*. The antimicrobial activity of sea fennel is given by the presence of falcarindiol which is a polyacetylene widely distributed within the *Apiaceae* family (Meot-Duros et al., 2010). The content of bioactives contributes to enrich sea fennel of many functional traits such as antioxidant, anti-inflammatory and anti-proliferative activity with great potential in nutraceutical and pharmaceutical sectors (Nartea et al., 2023).

CHAPTER 2
SEA FENNEL CULTIVATION

2.1 Cultivation and response to salinity stress

Sea fennel is a facultative halophyte. However, the optimum growth occurs in salt-free or low salinity environments (Kraouia et al., 2023). It grows well in sandy, well-drained soils with moderate to high salinity. It can tolerate poor nutrient conditions, making it suitable for coastal and marginal lands. The optimal climate is the Mediterranean one, with hot, dry summers and mild winters. The plant is characterized by low water requirements and the ability to thrive in full sunlight. It can survive on saline irrigation and can be propagated by growing the plants from seeds or cuttings (Castillo et al., 2022). Generally, a typical production of sea fennel in open field, like the one conducted in central Italy by the Rinci S.r.l., in the municipality of Castelfidardo, Ancona, (Figure 2-1), requires growing the seedlings in greenhouse. The seeds obtained from the sea fennel field are sown in plastic trays containing blonde peat above a top layer of vermiculite and irrigating them every day, two time a day for 8 minutes. After 21-30 days, the seeds germinate and mature in 5-6 weeks. The germinability is about 70-80%. Sea fennel cultivation follows a seasonal cycle. The resulting seedlings are transplanted on field between October and November.

The producer prepares the land by weeding and harrowing utilizing a milling machine and covering it with a plastic mulch. Cultivation of sea fennel on open field do not require irrigation as it can negatively affect the sensorial quality of the final product. Harvesting take place in the second year, starting in late May until June and early July. In this phase, that occurs manually, young leaves and shoots are harvested and transported to the facility to be processed. The plants regenerate producing new vegetative growth and reach the full flowering by August. In the dormant winter plants are cut at ground level to enhance a homogenous growth for the finest harvest in Aprile and May of the following season (Duca et al., 2024).

Figure 2-1 Cultivation of sea fennel on open field, in Marche Region. ((Rinci - Le Meraviglie Del Gusto*, n.d.).*

Some authors (Atia et al., 2006) studied the germination response of *C. maritimum* seeds to NaCl and sea water, as major salinity agents, to identify the threshold of salinity for a significant reduction in germination. Although sea fennel grows spontaneously in maritime environments, it has been demonstrated that the germinability is inhibited by salinity level over 50 mM of NaCl, and strongly affected over 5% of sea water in the medium., while is delayed with sea water at 5% and under increasing NaCl. The same consideration results considering the germination rate as it's reported on the Figure 2-2.

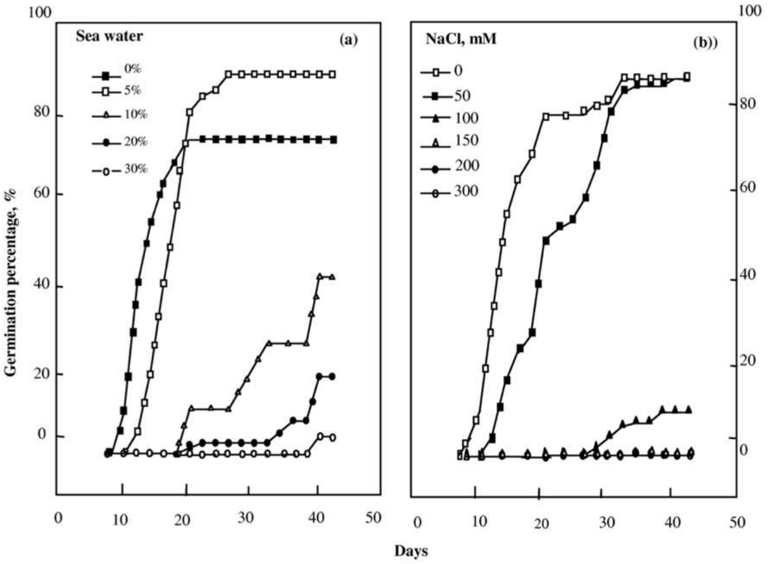

Figure 2-2 Effect of salinity (a: sea water, b: NaCl) on the germination (%) of Crithmum maritimum *(Atia et al., 2006).*

A few years later, it has been demonstrated that in natural conditions *C. maritimum* fruits are continuously exposed to various ions, including Na^{+}, Mg^{2+}, Ca^{2+}, Cl^{-} and SO_4^{2-} and the salt-induced inhibition of seed germination is salt-specific and could be classified in the following decreasing order: $MgCl_2$, $MgSO_4$, Na_2SO_4, NaCl. Magnesium salts are the most inhibitory, due to both osmotic stress and nutrient loss. Sodium salts inhibit the germination mainly through osmotic effects, but the germination of these seeds once transferred in distilled water suggests that in nature, sea fennel form a stock of seeds that germinate after winter rains, so that the plant can successfully establish (Atia et al., 2011; Castillo et al., 2022).

CHAPTER 3
THE LIFE CYCLE ASSESSMENT

3.1 **Introduction to Life Cycle Assessment**

Life cycle assessment (LCA) is a widely recognized framework that adhere to ISO 14040 and 14044 standards, where it is defined as the "*compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle*". LCA is used as an analytical tool to quantify all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services, considering the full life cycle, from the extraction of resources, through the production, use, recycling, up to the disposal of remaining waste. The environmental impact corresponds to the potential impact on the natural environment, human health or the depletion of natural resources, caused by the interventions between the technosphere and the ecosphere as covered by LCA (e.g. emissions, resource extraction, land use). It can have adverse effects on the air, land, water, fish and wildlife or inhabitants of the ecosystem and a direct link to public health and life quality issues (Abdallah, 2017; JRC, 2010).

Due to the limitation of raw material and energy resources, LCA has been used since the 1960 to find solutions for sustainable productions (Alhashim et al., 2021). LCA also helps to avoid resolving one environmental problem while creating others and avoid the "*shifting of burdens*" (when reducing the impact at one point of life cycle, there is an increase in the impact at another point).

To assess the environmental impact, LCA methodology is composed by four main steps: goal and scope, inventory analysis, impact assessment and interpretation of results.

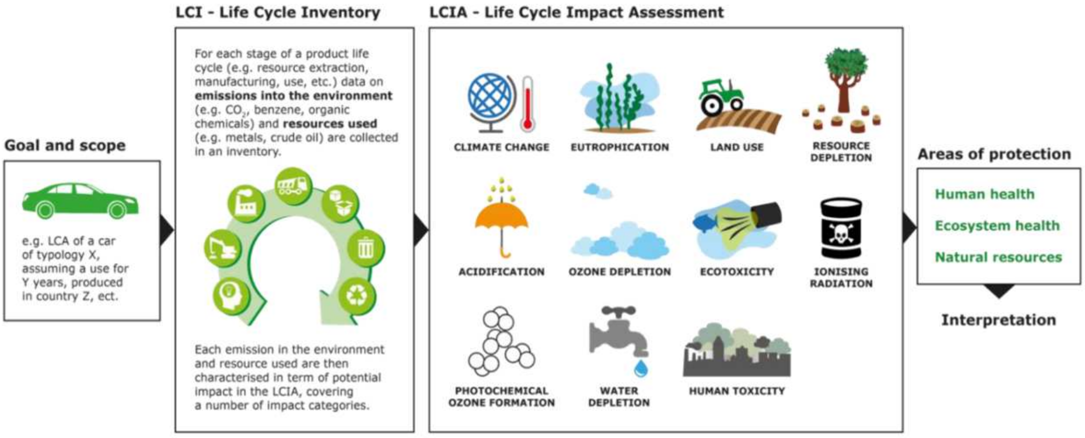

Figure 3-1 Life Cycle Assessment steps. *(Cristobal-Garcia et al., 2016).*

3.2 **Goal and scope definition**

Goal and scope definition is the step in which the following questions should be addressed: why perform LCA, who is the target audience, what is the product under the LCA study? In other words, in this phase is defined the aim of the study (e.g. estimate the impact from energy consumption), as well the intended application, (e.g. compare with different product\service), the reason for carrying out the study, (e.g. identification of hotspots in life cycle of a product, improvement on a specific step, brand report, decision support in policy development). Main methodological choices are made in this step: the functional unit, the system boundaries, the allocation procedures, the studied impact categories and the Life Cycle Impact Assessment (LCIA) model used. A functional unit is the reference unit in which elementary flows from the inventory until the impact assessment stage are represented. It represents the important basis that enables alternative goods or services to be compared and analysed (Alhashim et al., 2021; Rebitzer et al., 2004). The system boundaries determine which unit processes are included in the LCA analysis, and which are excluded. System boundaries are determined by an iterative process in which an initial system boundary is chosen, and then further refinements are made by including new unit processes that are shown to be significant by the sensitivity analysis (Li et al., 2014). System boundaries follow different approaches. The most used are:

- Cradle-to-Gate: from the extraction of raw material to the factory gate.
- Cradle-to-Grave: from the extraction of raw material to the waste disposal.
- Cradle-to-Cradle: from the extraction of raw material to the recycling process.

3.3 **Life Cycle Inventory (LCI) step**

Life Cycle Inventory step involves the data collection and the calculation procedure for the quantification of inputs and outputs of the studied system, concerning energy, raw material and other physical inputs, products, co-products, wastes, emissions to air, water, soil and other environmental aspects; it gives quantitative environmental information of a product throughout its entire life cycle. Inventory data sources can be primary and secondary. Primary data derived from surveys, interview, from real product, or reports. Secondary data are those deriving from previous studies or databases, (like Ecoinvent, GaBi, or IDEMAT) (Carmen Fernández Fernández, n.d.). The European Union defines secondary data as "*data that is not directly collected, measured, or estimated, but rather sourced from a third-party life-cycle-inventory database*". Data are elaborated and expressed based on the functional unit chosen in the previous phase (Alhashim et al., 2021; Cristobal-Garcia et al., 2016). In LCA terms primary data is called "*foreground system*" that includes all necessary raw inputs of a product's lifecycle that are then connected to corresponding impacts in an LCA. They are mainly used for Attributional-LCA approach. Secondary data refer to the so-called "*background system*". They are more accessible and allows to get LCAs faster, providing a good indication of impact hotspots where is needed to be focused on improvements and sustainability research. The main drawback lays on the lack of accuracy and authenticity of data, since they do not come directly from suppliers or measurements. Therefore, the LCA results are expected to be more generic and not completely "true-to-reality". Background data can vary when used in Consequential-LCA approach. In fact, the C-LCA includes processes that are expected to be affected on short and\or long term by the decisions supported in the study. It typically involves the system expansion including downstream and upstream processes. In other words, it takes into account the consequence of decisions and changes on a system (e.g. switching to renewable energy); particularly, how modifying a system will affect the environment over time, including the market effects (increasing demand, price fluctuations, technology used, supply chain dynamics).

The Attributional Lyfe Cycle Inventory methodology aims at describing the environmentally relevant physical flow to and from a product or process. There is a lack of market perspective in which changes may induce domino-effects (*Ecochain*, n.d.; Ekvall & Weidema, 2004). The A-LCA aims at understanding the current situation and to identify hotspots and potential improvement options within a static context. In attributional LCA, when the process produce more than one product, it is necessary to divide the environmental impacts from the process between the products. This method is called "*allocation*". According with the ISO 14040 standard, allocation is defined as "*the partitioning of material and energy flows (input and output) to or from an activity to the product system under study, to allocate environmental burdens or benefits among different products and co-products*". It can be performed from economic, energy or weight point of view (Ekvall, 1999).

3.4 **Life Cycle Impact assessment (LCIA)**

Life Cycle Impact assessment is the phase in which the Life Cycle Inventory results are associated to environmental impact categories and indicators to evaluate its magnitude and significance, based on inputs and outputs defined in the inventory phase. Essentially, it translates raw data (e.g. emissions, resource use) into understandable *Environmental Impacts Categories*, when Midpoint method is used, (e.g. Climate change, Ozone depletion, Acidification, Eutrophication, etc..), or into the three *Area of Protection* for the Endpoint method, (Human health, Ecosystem quality and Resource depletion), as reported in the Figure 3-2.

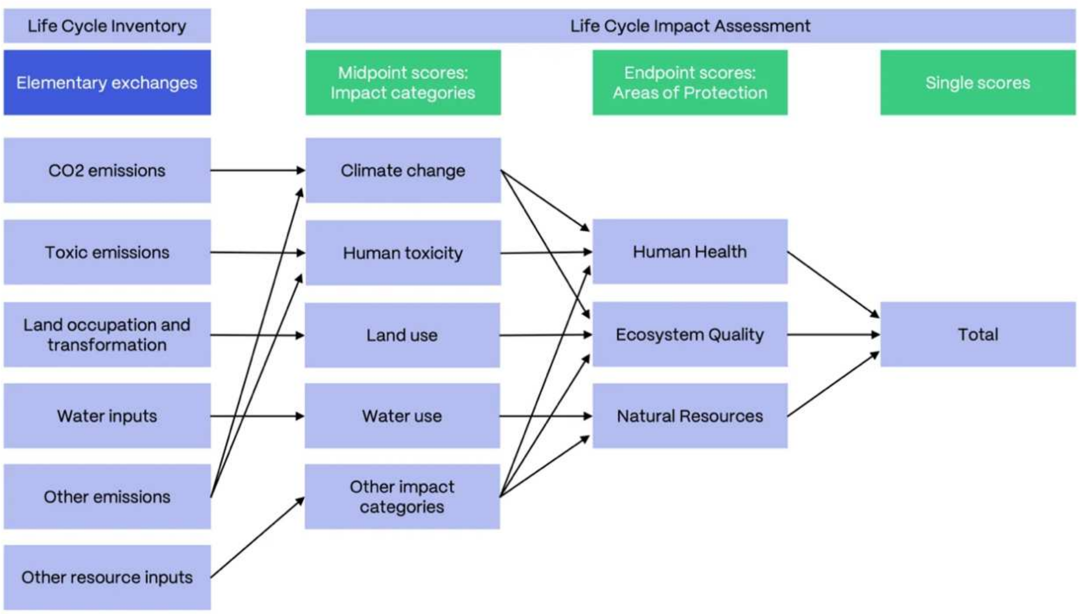

Figure 3-2 Midpoint and Endpoint methodology for Life Cycle Impact assessment. (Ecoinvent Support, n.d.).

Life Cycle Impact assessment includes four additional sub-steps: classification, characterization, normalization and weighting. (European Commission, 2010; JRC, 2010).

3.4.1 Classification

Classification means to assign all elementary flows of the inventory to one or more impact categories to which they contribute and that were selected for the impact assessment in the scope definition of the study. Characterization is the step in which all classified elementary flows are assigned to its characterization factor that express how much that flow contributes to the impact category indicator: for each impact category separately, the LCIA indicator is calculated by multiplying the amount of each contributing elementary flows of the inventory with its characterization factor. The results may be summed up per impact category, and not across impact categories.

3.4.2 Normalization

Normalization is an optional step under ISO 14044:2006, in which life cycle impact assessment results are divided by normalization factors to get for each impact (for midpoint approaches) or area of protection (for endpoint approach), the relative share of the impact of the analysed system per average citizen or globally, per country, per person in one year, etc. Normalization supports the interpretation of the results of the study.

3.4.3 Weighting

Weighting is another optional step that assigns different level of importance to different impact categories based on their perceived relevance or social values. It’s done by multiplying the normalized results by a set of weighting factors (in %). The results of this step can support the interpretation of the results and help in decision-making. However, weighting is subjective, and different stakeholders may have different options on how to prioritize impact categories (European Commission, 2010; JRC, 2010).

3.5 **Interpretation of results**

The last phase of the LCA is defined from ISO as “*the phase in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations*”. The primary purpose of interpretation is to evaluate the starting point for the product improvement, understanding the process tree and then identifying key issues, i.e., the key processes, materials, activities, or even life cycle stages in developing a product. Once identified the main hotspots on the life cycle of a product, some recommendations and more environmentally friendly designs and\or process modification are suggested (Alhashim et al., 2021). This phase is iterative, meaning that, it involves both assessing the results and reviewing the entire study if inconsistency or uncertainties are found that could influence the conclusion. It helps guide the study by ensuring that each step aligns with the overall objectives defined in the goal and scope definition phase. Contribution analysis and sensitivity analysis are performed as a part of the interpretation step to help in understanding the main drivers of environmental impact and assessing the robustness of the results. The contribution analysis assesses which processes, material, emissions or life cycle stages drive the biggest impact (*Ecochain*, n.d.). The contribution analysis is performed by attributing for each life cycle stage the percentage contribution to each impact category, and then, show which stages have the highest percentage. The sensitivity analysis has the purpose to assess the reliability of the final results and if included, of the conclusion and recommendations of the LCA study (JRC, 2010).

There are different methods to conduct the LCA analysis. The main used are: Environmental Footprint method v3.0, CML-IA, ReCiPe 2016, ILCD 2011 Midpoint+, EPD (2013). Also, being very complex, LCA analysis are performed by using dedicated software to facilitate the environmental impact assessment, as well the inventory phase and the interpretation of results. The most used software is the *SimaPro*. (Carmen Fernández, n.d.).

CHAPTER 4
MATERIALS AND METHODS

4.1 **Introduction**

The present chapter provides a detailed account of the approaches, tools and methods used to achieve the set goals of this work in assessing the environmental performance of new sea fennel products in the design phase by the Rinci S.r.l. at Castelfidardo municipality (AN), in Marche region. These products are represented by "*fermented sea fennel in brine*" and "*sea fennel spice*". More specifically, the chapter provides the goal and scope definition, the functional unit, the system boundaries, data collection and system boundaries comprising the main feature of the product flows under analysis, it lists the used environmental impact indicators and the used LCA methodology.

4.2 **Goal and scope definition**

The aim of the present study is to evaluate the environmental performance of new product based on sea fennel cultivated in open field system from the Rinci S.r.l. in central Italy, to

- identify the main hotspot and potential process improvement,
- make comparison between the most used preserves.

The functional unit used for each type of product under study is:

- 30 gr of packed sea fennel spice
- 1 jar of 100 g of packed fresh fermented sea fennel in brine,
- 1 jar of 100 g of packed pasteurized fermented sea fennel in brine.

4.3 **System boundaries and data collection**

The first activity has been a visit to the Rinci facility to obtain the foreground inventory data, making detailed and in-depth questionnaire to the owner of the company in order to build the process flow resulting in the final products. From the first questionnaire emerged the steps of the process for the products under study, energy flows, ingredients and type of packaging. After an initial analysis of the acquired information, a flow diagram of the products under study has been defined and a list or raw data has been compiled to create a draft of the inventory table. Notwithstanding the detailed first interview, further clarification was needed, and other questions have been sent to the producer to have the highest degree of precision in defining the mass and energy flow of production, resulting in a better environmental performance evaluation. Background data for ancillary materials and energy have been obtained from the Ecoinvent database version 3.9. The system model used was "*Allocation cut-off by classification*", (meaning that the environmental burden of processes is associated only to the main product up to the point where a by-product or waste is generated, excluding certain burdens associated with other processes, which are "cut-off" from the system). Once raw data have been acquired and the functional unit defined for each product under study, it has been necessary to convert raw data based on the functional unit and built the Life Cycle Inventory table, that will be described in the following chapter. Below are reported the descriptions of the process for sea fennel spice and fermented sea fennel products.

4.3.1 Sea fennel spice

Data for the sea fennel spice product is structured into: the transport of the raw material that is sea fennel fresh biomass, drying, milling, packaging (including primary, secondary and tertiary packaging materials) and potential distribution. The process flow and LCA system boundary (dotted part) of this product in represented in the Figure 4.1. Fresh sea fennel biomass is transported from the field to the facility for an average distance of 20 km. The drying process is carried out in big stainless-steel boxes using a 10kW drier, for 7 days, getting about 18% of dried mass. Dried biomass is transferred into big bags and transported to the mill. The milling step does not occur is the same facility. The packaging consists in a glass container of 10 cl volume with a perforated plastic cover made of polypropylene.

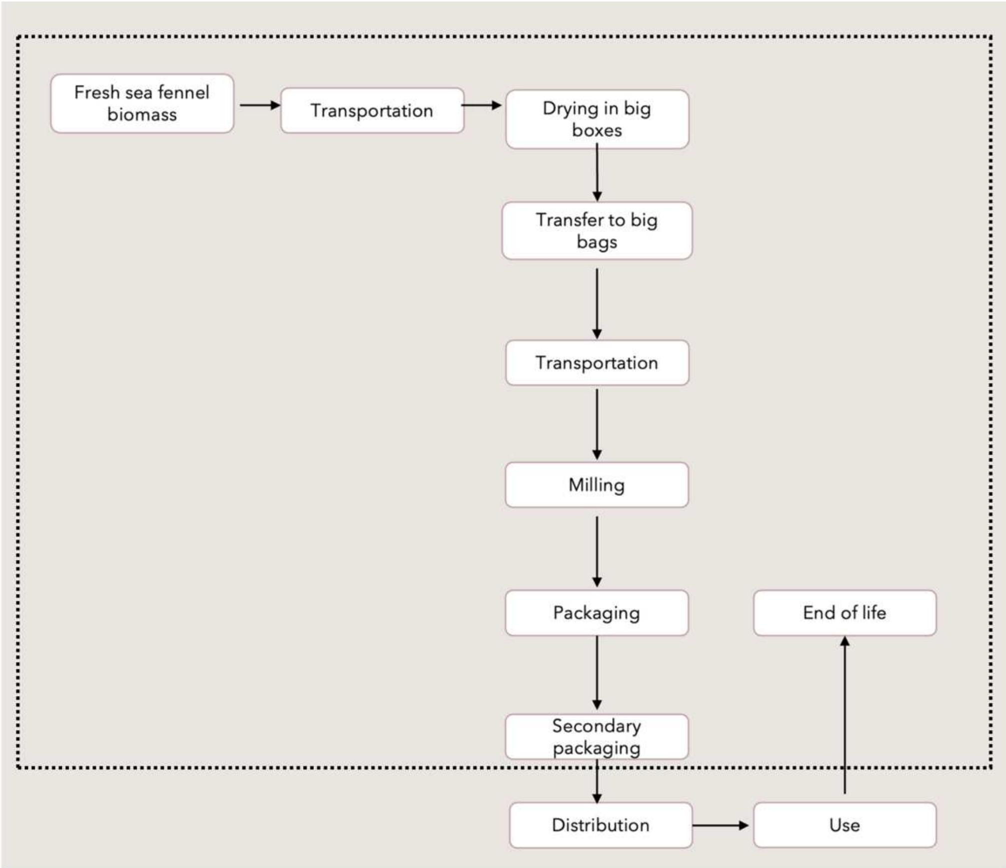

Figure 4-1 LCA system boundary and process flow of sea fennel spice.

4.3.2 Fermented sea fennel

Data is structured into: transport of sea fennel fresh biomass, processing, packaging, distribution and waste management. For this product two different scenarios have been considered:

- First scenario: the fermented product is stabilized by pasteurization which makes it stable on the shelf. The process diagram and system boundary for the first scenario is represented in Figure 4-2. More in detail: the fresh sea fennel biomass undergoes manual sorting. We assumed 5% losses from this step. It follows the washing step using current water to eliminate powder, debris, insects, and any physical contaminants, the blanching step of 25 kg of fresh sea fennel per cycle using 15 litres of water. Blanching occurs at 90°C and helps softening the sea fennel leave tissues opening stomata and enhancing the fermentation. The cooling step uses current water to avoid microbial contamination. The fermentation step occurs in stainless-steel drum (220 litres of capacity). For each cycle 50 kg of raw sea fennel are fermented by adding 0,01 kg of microbial starter of lactic acid bacteria, 150 litres of water, 1,5 kg of fructose and 10,5 kg of NaCl. Fermentation lasts 2 months (more than the actual time needed) to obtain a good balance between flavours and acidity. It follows the washing step to reduce salt concentration from 5% to 2%, then the product undergoes pasteurization, cooling and packaging. The final product does not require refrigeration until the opening of the jar. There are 100 gr of fermented sea fennel and 100 gr of brine at 2% salt concentration.

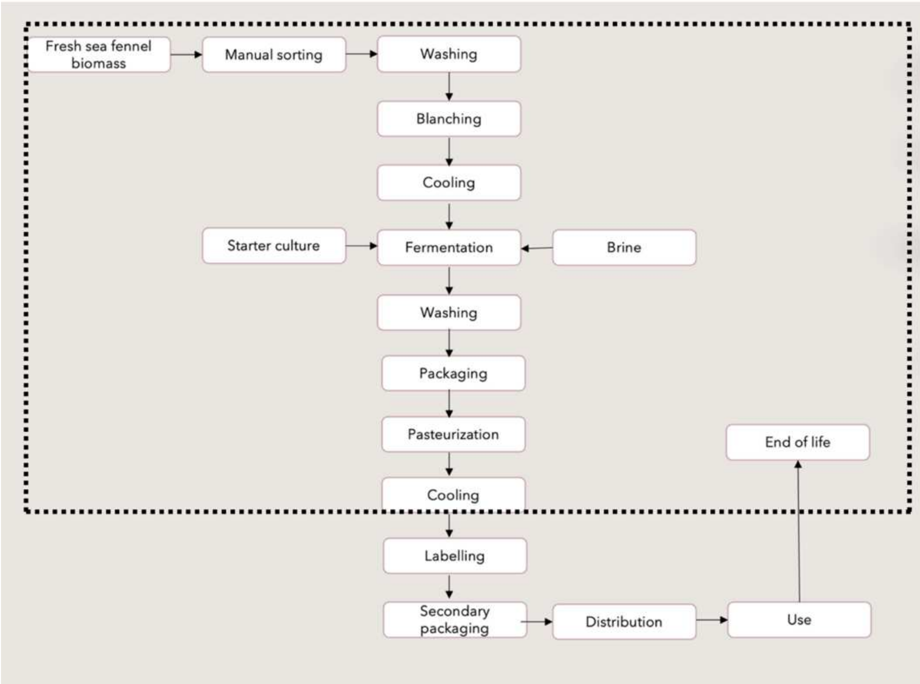

Figure 4-2 First scenario: LCA system boundary and process flow of pasteurized fermented sea fennel.

- Second scenario: the product does not undergo heat treatment after fermentation but is stabilized by a higher salt concentration and the application of the cold chain. The process flow is the same until the ended fermentation, followed by the increasing of salts concentration from 5% to 8% to stabilize the product and stop the fermentation. The product is packed in glass jar closed by metal lid containing 100 gr of fermented sea fennel and 100 gr of brine with 8% of salt concentration.

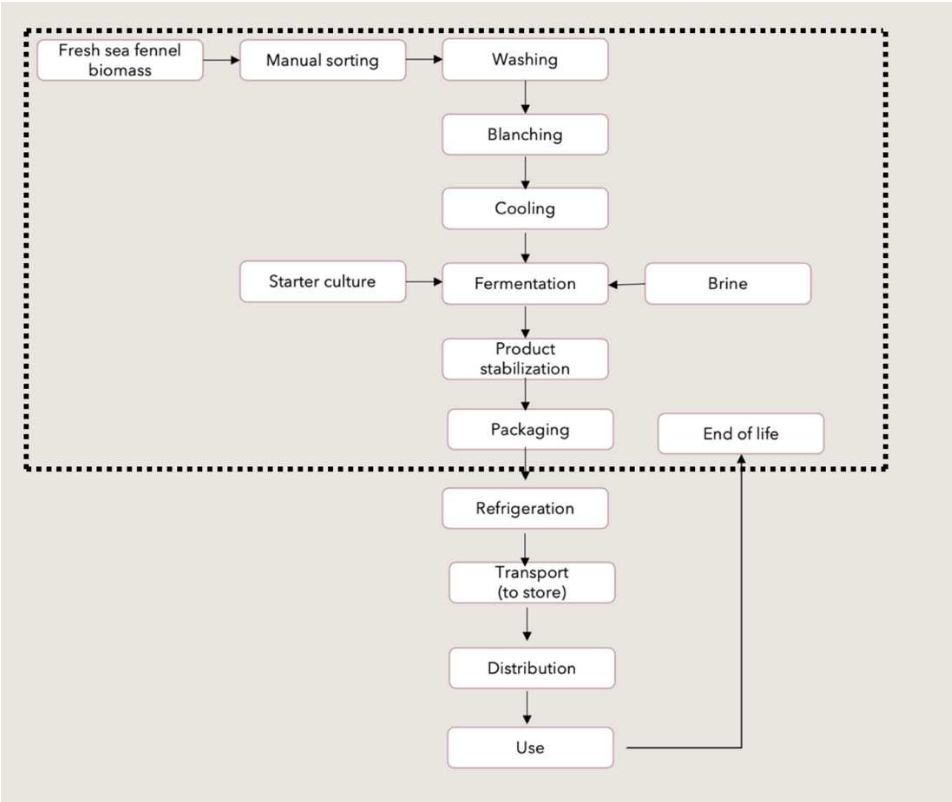

Figure 4-3 Second scenario: LCA system boundary and process flow of fresh fermented sea fennel stored in refrigerated condition.

4.4 **Life cycle impact assessment**

The analysis has been carried out by using data resulting from the life cycle inventory table, which have been elaborated by the *SimaPro* software. Attributional LCA has been performed using the Environmental Footprint (EF) 3.0 midpoint life cycle impact assessment method. The impact of sea fennel-based products, per the selected functional units, has been evaluated 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 (HTCN), 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).

The interpretation of results includes contribution analysis of phases and key processes and sensitivity analysis. Regarding the sensitivity analysis, it has been considered the scenarios of reducing packaging glass of 10%, 20% and 30% for the three products under study. Furthermore, it has been considered the scenario of refilling sea fennel spice packaging. For the fermented products it has been considered the different use in terms of refrigeration time. More details are exposed in the following chapter 5, about results and discussions.

CHAPTER 5
RESULTS AND DISCUSSIONS

The chapter presents and discusses the resulting Life Cycle Inventory table for each product under study and the midpoint LCIA results for the three types of sea fennel-based products. The products under study have never been produced from the manufacturer. Therefore, the results have not been compared with analysis of analogue productions, reason why the study focuses on the comparison with similar products abundantly present on the food market. The environmental impact of sea fennel spice has been compared with the one of the turmeric and chili powder production in Indonesia from PT X, a medium-size business that manufactures spices and seasonings for the food industry. The results for this product have been collected from the study conducted by the Department of Agro-Industrial Technology, Faculty of Agricultural Technology of the Gadjah Mada University, in Indonesia (Ayu Kurniawati et al., 2023). The environmental impact of both fresh and pasteurized fermented sea fennel has been compared with those reported on the Environmental Product Declaration (EPD) of Borlotti Beans made by Cirio company (International EPD system, n.d.).

5.1 LCIA results for sea fennel spice

Table 2 shows the inventory table for producing 30 g of packed sea fennel spice. Plastic waste management was modelled as 29% recycling, 61% incineration and 10% landfilling. Glass waste management was modelled as 79% recycling and 21% landfilling. Transport of fresh sea fennel biomass has been considered including the distance between the field and the facility, which correspond to 20 km by lorry 7,5-16 metric ton.

Table 2 Life cycle inventory table to produce 30 g of sea fennel spice.

Life Cycle Inventory table		
	Unit\FU	Value
Input		
Plastic boxes	kg	1,77E-04
Fresh sea fennel biomass	g	1,64E+02

Energy for drying:		
Natural gas	m3	1,25E-02
Energy (electricity)	kWh	9,16E-02
Energy for milling	kWh	6,00E-02
Polypropylene bags	kg	1,77E-04
Packaging		
Sea fennel spice	g	3,00E+01
Glass container (10 cL vol)	g	1,15E+02
Perforated plastic cover (PP)	g	5,20E+00
Plastic film (secondary packaging)	g	3,25E-01
Landfilling glass container	g	2,42E+01
Landfilling plastic cover	g	5,53E-01
Incineration plastic cover	g	3,37E-01
Recycling glass container	g	9,12E+01
Recycling plastic cover	g	1,60E+00

The total midpoint impact assessment scores of 30 gr of packed sea fennel spice are reported in Table 4. Concerning climate change, the total CC score is 0,248 kg CO_2 eq. The analysis includes both direct and indirect emissions.

The figure 5-1 shows a graphic representation of the LCIA results in stacked bar chart, illustrating the contribution analysis to produce the spice. The packaging glass had the most significant environmental impact across most categories. The highest contribution is for particulate matter impact category (84,8%), followed by ecotoxicity fresh water (73,8%), and acidification (72,2%). It shows more than 45% of contribution for all the impact category excepted for IR, OD, RUF, RUM and WU. After packaging glass, the second most significant impact is related to the electricity used for drying fresh sea fennel biomass, which shows the highest contribution (43%) for water use impact category (WU) followed by resource use, minerals and metals (RUM), and ionizing radiation (IR) for about 30%. The input of fresh biomass sea fennel shows the highest value for land use (LU) impact category as we could expect, having almost 92% of contribution. Waste management had the lowest overall impact due to credits received from recycling glass and plastic. The highest impact, considering waste management is given by the incineration of polypropylene plastic cover for climate change impact category.

Figure 5-2 shows the network analysis obtained from the *SimaPro* software, highlighting how inputs and outputs are linked across different stages of the product's life cycle.

Table 3 The midpoint impact scores of 30 g of packed sea fennel spice.

Impact category	**Unit**	**Score**
Acidification	mol H+ eq	1,42E-03
Climate change	kg CO2 eq	2,48E-01
Ecotoxicity, freshwater	CTUe	1,11E+00
Particulate matter	disease inc.	1,72E-08
Eutrophication, marine	kg N eq	2,41E-04
Eutrophication, freshwater	kg P eq	3,84E-05
Eutrophication, terrestrial	mol N eq	2,68E-03
Human toxicity, cancer	CTUh	9,63E-11
Human toxicity, non-cancer	CTUh	2,51E-09
Ionising radiation	kBq U-235 eq	1,44E-02
Land use	Pt	1,88E+01
Ozone depletion	kg CFC11 eq	5,12E-09
Photochemical ozone formation	kg NMVOC eq	9,27E-04
Resource use, fossils	MJ	3,65E+00
Resource use, minerals and metals	kg Sb eq	1,33E-06
Water use	m3 depriv.	5,12E-02

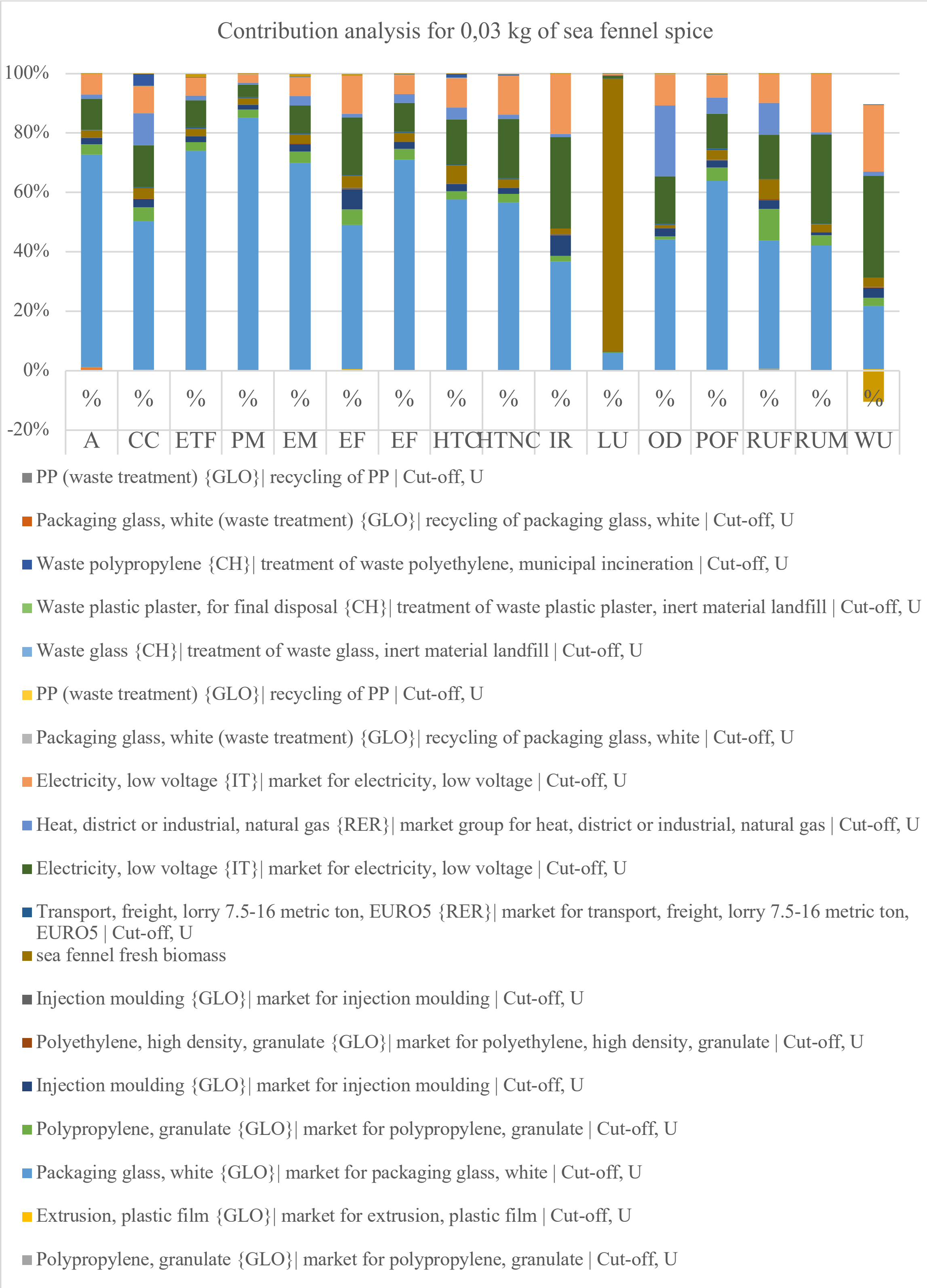

Figure 5-1 The overall contribution of the various input for producing 30g of packed sea fennel spice.

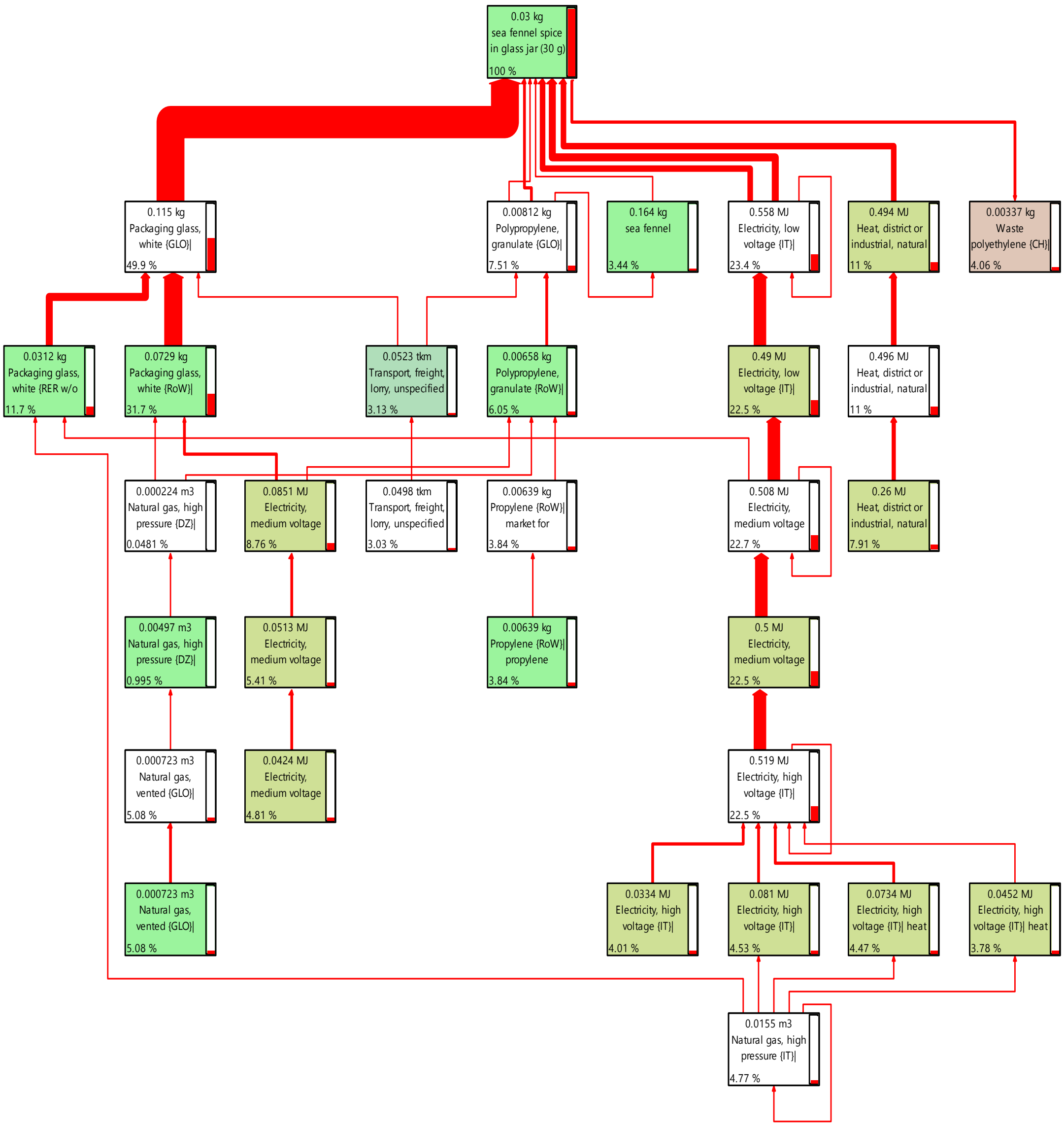

Figure 5-2 Network analysis for producing 30 g of packed sea fennel spice, (cut-off 3%).

5.1.1 Comparison of the result with similar product

Results has been compared with the results of environmental impact of producing turmeric and chili powder at PT X, an Indonesian spice manufacturer, using Life Cycle Assessment methodology (Ayu Kurniawati et al., 2023). In their gate-to-gate analysis, they considered the purchasing raw materials to turn into goods before being delivered. The process flow includes stripping, grinding, sifting, mixing, oven drying and cooling having similarity with the sea fennel spice production. To produce 1 kg of turmeric powder the score for the Global Warming Potential is 0,7627 kg CO_2 eq. The score for 1 kg of sea fennel corresponds to 8,27 kg CO_2 eq. The energy required for turmeric powder correspond to 7.963 MJ and for chili powder 8,506

MJ. For 1 kg of sea fennel spice the energy required has similar order of magnitude and correspond to 15.4 MJ. The GWP value for the considered Indonesian spices are attributed to CO_2 emissions during raw material procurement for fuel consumption. While, for sea fennel spice, the main contribution for the climate change impact category is given by the packaging glass. However, the study performed by Ayu Kurniawati et al, does not specify packaging material typology neither contribution analysis making difficult to produce further comparison.

5.1.2 Scenario analysis for packaging

Due to the relatively high impacts of the packaging for the considered se fennel spice constituted by white glass container and polypropylene perforated cup, four different scenarios have been considered: reducing packaging glass of about 10%, 20% and 30% and the possibility to reuse the packaging, by refilling. In the latter case it has been considered the delivering of 1 kg of sea fennel spice in a plastic sachet of 15 grams and refilling the same packaging unit for about 33 times. The LCA results for the four scenarios are represented in the Figure 5-2. Considering the CC, the score resulting from the reduction of packaging glass of 10%, 20%, 30% do not differ much. Further reduction on the thickness of glass container could not be considered for the plausible use of the packaging type: it will be too much fragile. A great reduction on the score is obtained considering the possibility to refill the packaging, which correspond to about 60% of the original results.

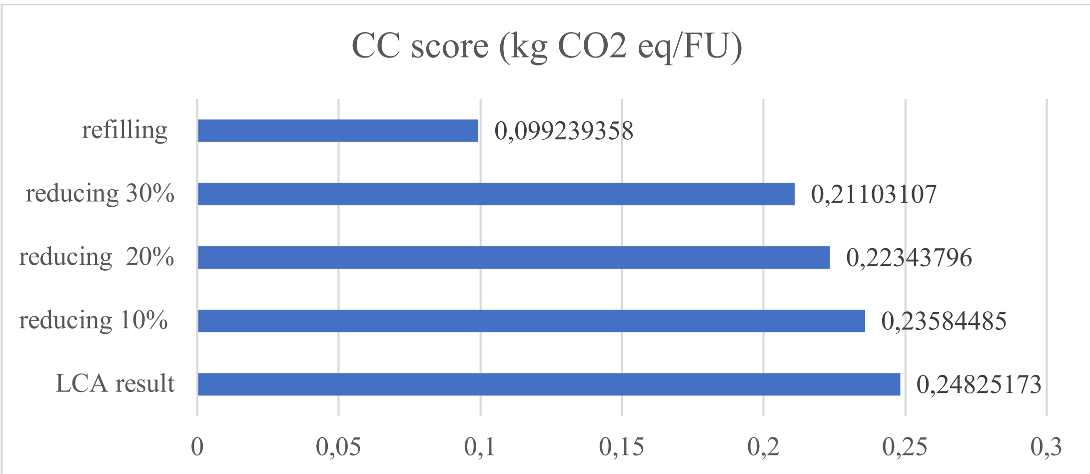

Figure 5-3 Comparison of climate change score between original results and the alternative scenarios results.

5.2 **LCIA results for fermented sea fennel**

Table 5 shows the life cycle inventory table to produce 1 jar of both fresh and pasteurized fermented sea fennel. Glass waste management was modelled as 79% recycling and 21% landfilling. Metal lid (tin plate) waste management was modelled as 82% recycling and 18% landfilling. The transport of fresh sea fennel biomass has been considered including the distance between the field and the facility, corresponding to 20 km by lorry 7,5-16 metric tons. Secondary data have been used for energy and water required for the pasteurization step (Djekic et al., 2014).

Table 4 Life cycle inventory table to produce 1 jar of 100 g of fermented sea fennel: (pasteurized on the left; stabilized by salt on the right).

Fresh fermented sea fennel in brine				**Pasteurized fermented sea fennel in brine**		
	Unit\FU	Value			Unit\FU	Value
Input				*Input*		
Plastic boxes	*kg*	*0,00012*		*Plastic boxes*	*kg*	*0,00012*
Fresh sea fennel biomass	*g*	*105,26*		*Fresh sea fennel biomass*	*g*	*105,26*
Water (washing)	*l*	*0,6*		*Water (washing)*	*l*	*0,6*
Water (blanching)	*l*	*0,06*		*Water (blanching)*	*l*	*0,06*
Energy (blanching)	*kWh*	*0,0003*		*Energy (blanching)*	*kWh*	*0,0003*
Water (cooling)	*l*	*0,6*		*Water (cooling)*	*l*	*0,6*
Fermentation:				*Fermentation:*		
Salt (NaCl)	*g*	*21*		*Salt (NaCl)*	*g*	*21*
Sugar (fructose)	*g*	*3*		*Sugar (fructose)*	*g*	*3*
Water	*l*	*0,3*		*Water*	*l*	*0,3*
Microbial starter (LAB)	*g*	*0,02*		*Microbial starter (LAB)*	*g*	*0,02*
				Salt (NaCl for stabilization)	*g*	*9*
Pasteurization:						
Energy	*kWh*	*0,009*				
Water	*l*	*0,25*				
Water (cooling)	*l*	*0,25*				
Packaging:				*Packaging:*		
Fermented sea fennel	*g*	*100*		*Fermented sea fennel*	*g*	*100*
Glass jar	*g*	*189*		*Glass jar*	*g*	*189*
Metal lid (tin plate)	*g*	*15*		*Metal lid (tin plate)*	*g*	*15*
Brine 2%	g	100		Brine 8%	g	100

Recycling metal lid	*g*	*12,3*		*Recycling metal lid*	*g*	*12,3*
Recycling glass jar	*g*	*149,31*		*Recycling glass jar*	*g*	*149,31*
Land filling glass jar	*g*	*39,69*		*Land filling glass jar*	*g*	*39,69*
Land filling metal lid	*g*	*2,7*		*Land filling metal lid*	*g*	*2,7*

The total midpoint impact scorer for 1 jar of fresh fermented sea fennel and pasteurized fermented sea fennel are reported in the Table 5. Concerning the climate change score, it corresponds to about 0,38 kg CO_2 equivalents for both production type. The scores for each impact category considering the two product which only differ on the additional pasteurization step results very closed each other, with any significant variation. But it's important to stress the fact that the performed analysis is gate-to-gate, and it's necessary to consider the different use of the products resulting from the two considered scenario:

- In the first scenario, pasteurized fermented fresh sea fennel the product does not require cold chain during distribution and once at home, the consumer have to refrigerate it after opening.
- In the second scenario, fresh fermented sea fennel does not undergo pasteurization. The product undergoes to stabilization step that increase the concentration of salt in the brine from 5 to 8% to slow down the fermentation and it requires cold chain distribution to prevent spoilage phenomenon and the growth of pathogenic microorganisms.

This consideration has been taken into account during the sensitivity analysis and it is exposed in the subchapter 5.2.2.

Table 5 The midpoint impact score for 1 jar of 100 g of fresh fermented sea fennel (FFSF) and pasteurized fermented sea fennel (PFSF).

	Unit	**Score**	
Impact category		*FFSF*	*PFSF*
Acidification	*mol H+ eq*	*3,74E-03*	*3,74E-03*
Climate change	*kg CO2 eq*	*3,80E-01*	*3,81E-01*
Ecotoxicity, freshwater	*CTUe*	*6,18E+00*	*6,16E+00*

Particulate matter	*disease inc.*	*4,72E-08*	*4,71E-08*
Eutrophication, marine	*kg N eq*	*7,64E-04*	*7,63E-04*
Eutrophication, freshwater	*kg P eq*	*4,21E-04*	*4,21E-04*
Eutrophication, terrestrial	*mol N eq*	*9,50E-03*	*9,49E-03*
Human toxicity, cancer	*CTUh*	*2,64E-10*	*2,64E-10*
Human toxicity, non-cancer	*CTUh*	*1,29E-08*	*1,29E-08*
Ionising radiation	*kBq U-235 eq*	*2,47E-02*	*2,50E-02*
Land use	*Pt*	*1,46E+01*	*1,46E+01*
Ozone depletion	*kg CFC11 eq*	*5,76E-09*	*5,82E-09*
Photochemical ozone formation	*kg NMVOC eq*	*2,42E-03*	*2,42E-03*
Resource use, fossils	*MJ*	*4,88E+00*	*4,91E+00*
Resource use, minerals and metals	*kg Sb eq*	*4,05E-04*	*4,05E-04*
Water use	*m3 depriv.*	*-4,91E-02*	*-7,30E-03*

The Figure 5-4 shows the LCIA results in stacked bar chart, illustrating the contribution analysis to produce 1 jar of fresh fermented sea fennel in brine. The packaging glass and tin have the most significant environmental contribution across all impact categories. Glass shows the highest contribution for CC, PM, LU, OD, RUF and WU. While tin has the highest contribution for A, EFT, EM, EF, ET, HTC, HTNC, IR, POF and RUM. Results show a negative value of environmental impact regarding tin for water use impact category. The reason lays on the fact that during tin mining the resulting by-product is implied in the industrial wastewater treatment. The Figure 5-5 shows the contribution analysis regarding the production of 1 jar of pasteurized fermented preserve, with very similar results. Figure 5-6 and 5-7 represent the network analysis for both scenarios.

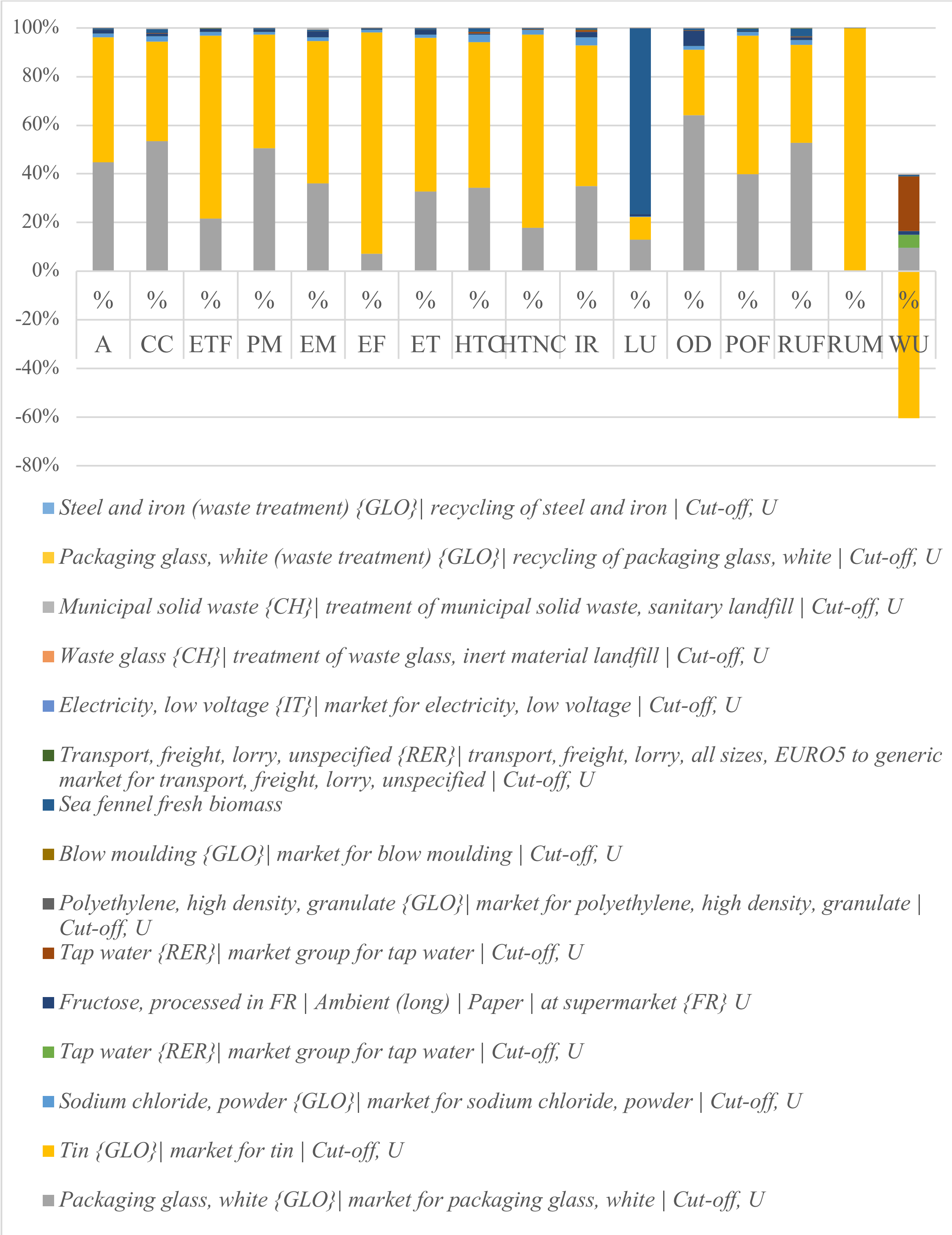

Figure 5-4 The overall contribution of the various inputs for producing 1 jar of 100 g of fresh fermented sea fennel in brine.

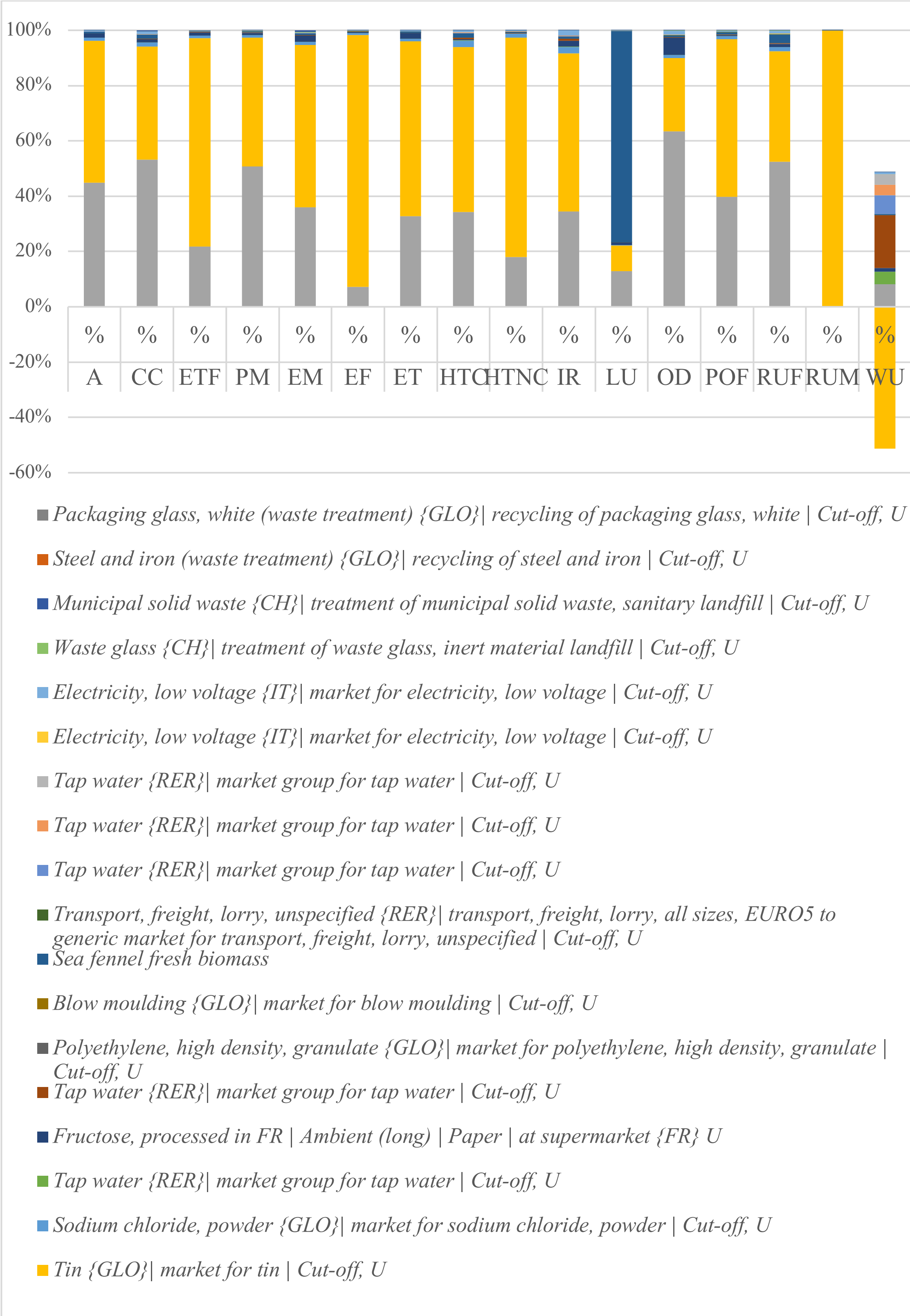

Figure 5-5 The overall contribution of the various input for producing 1 jar of 100 g of pasteurized fermented sea fennel in brine.

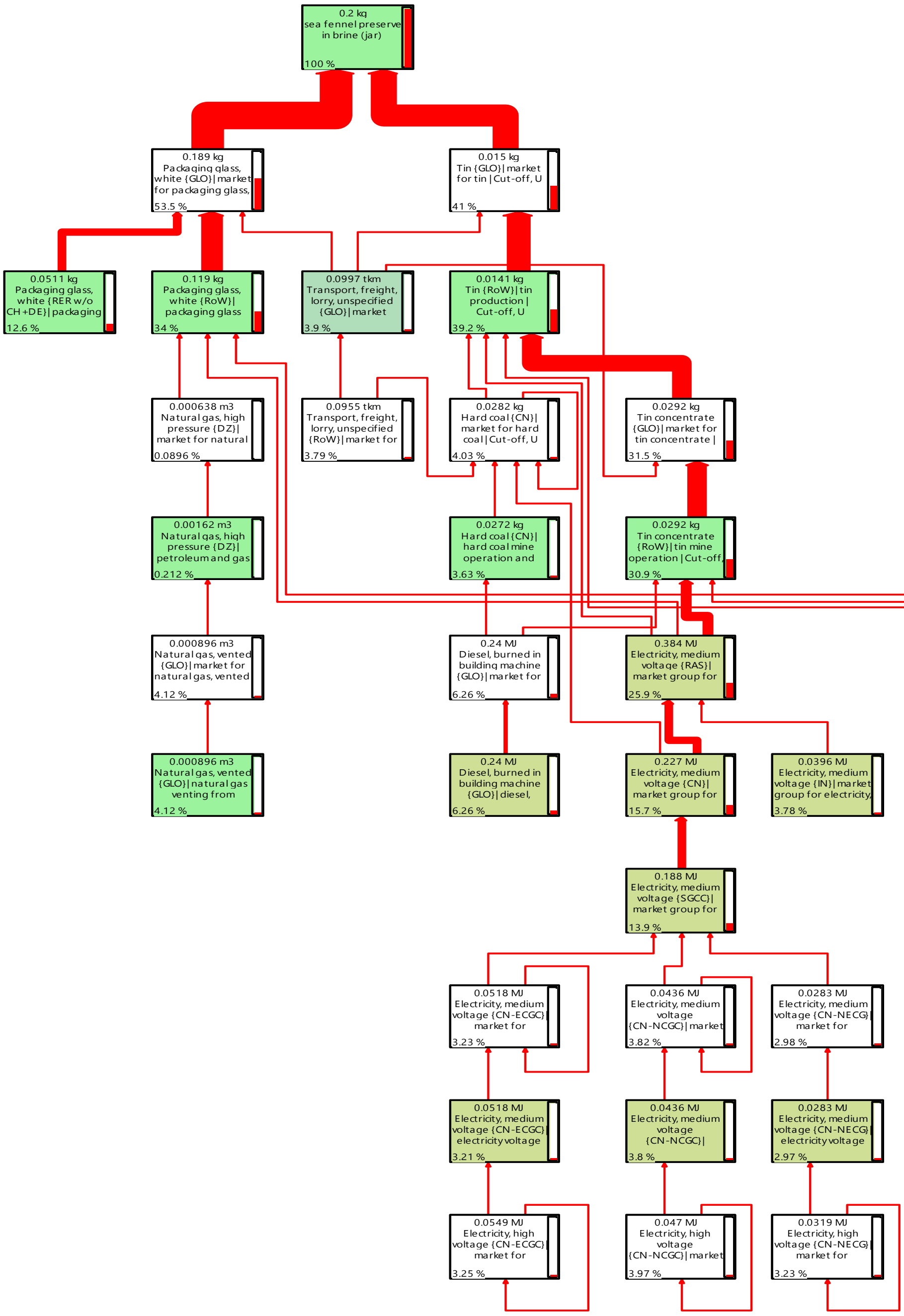

Figure 5-6 Network analysis for producing 1 jar of 100 g of packed fresh fermented sea fennel, (cut-off 3%).

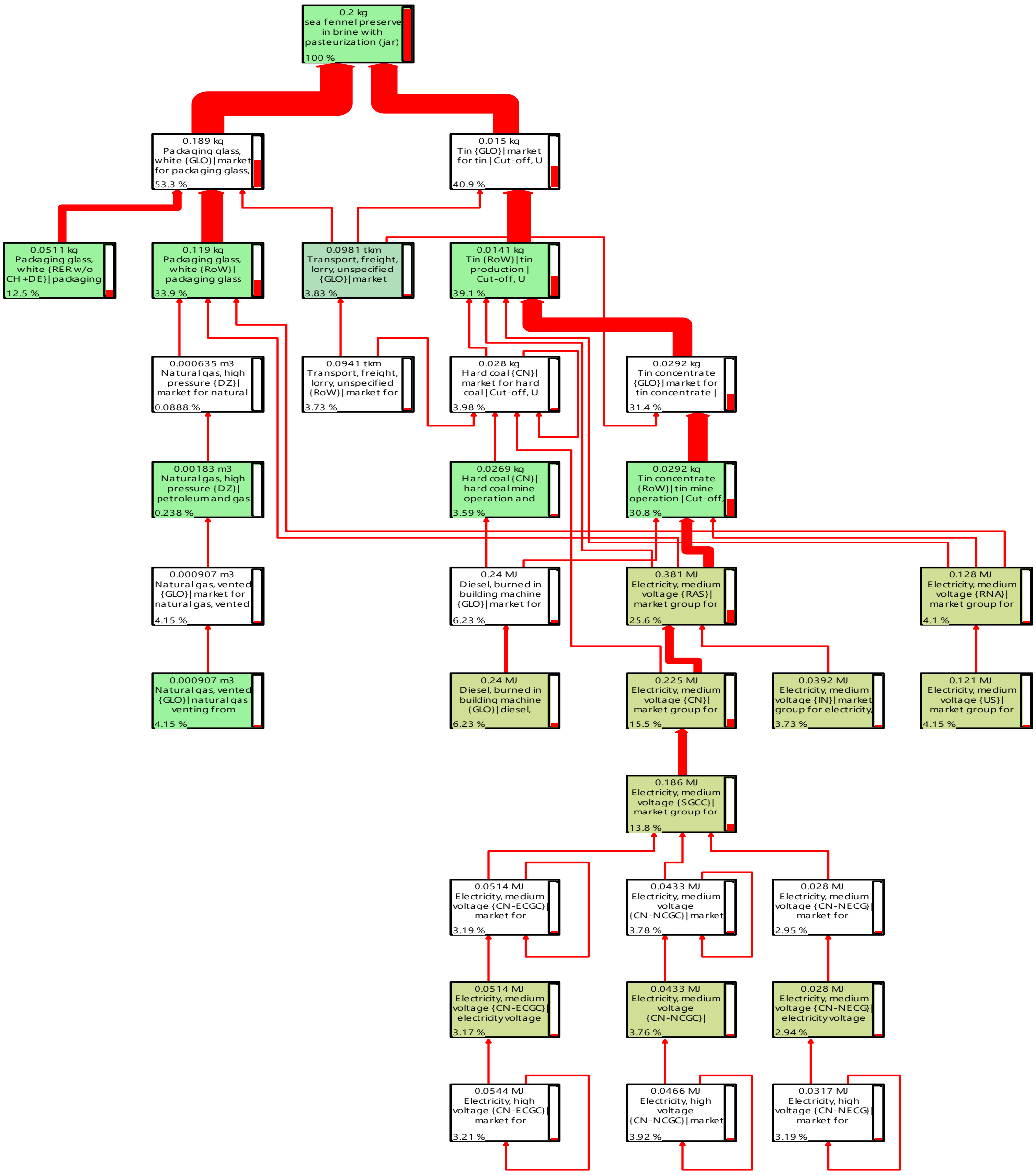

Figure 5-7 Network analysis for 1 jar of 100 g of packed pasteurized fermented sea fennel in brine, (cut-off 3%).

5.2.1 Comparison of the results with similar product

In the present subchapter the environmental impact results are compared with the official results derived from the Environmental Product Declaration (EPD) of Borlotti beans in glass jar produced by Cirio company. The EPD is a document verified and registered that communicates transparent and comparable information about the environmental performance of a product evaluated along its life cycle, which is calculated through the LCA analysis,

following the ISO 14040 series. It's based on the ISO Standard 14025. For the purposes of the present study, the choice of comparing the results for sea fennel preserve with the cited EPD document, lays on the similarity of the two products. In fact, both are preserved vegetable stored in glass jar with brine solution (water and salt). The declared unit is 1 kg of packed Borlotti beans in glass jar 370 g. System boundaries include upstream process (cultivation phase and production of ingredients and packaging material), core process which include transport, process, packaging and wastewater treatment, and downstream processes (distribution of final product and primary packaging end of life). The product comes from plant that for the processing line use only certified electricity from renewable sources, implement the recovery of water and its purification, (average rate about 33%). The distribution is modelled at European level. All packaging used is 100% recyclable. The total score for the Global Warming Potential (GWP) resulting from the EPD is 1,12 kg CO_2 eq. To render the results between borlotti beans and fermented sea fennel regarding CC comparable has been necessary to subtract the contribution of distribution from the borlotti bean score, (which correspond to 0,07 kg CO_2 eq.) and add the midpoint impact score of 1 kg of freshly harvested sea fennel at the farm gate, from the literature (which correspond to 0,07 kg CO_2 eq. (Duca et al., 2024), to the score for 1 kg of fermented sea fennel.
The final score for the climate change of 1 kg of packed borlotti beans is 1,05 kg CO_2 eq. The final score for climate change impact category for 1 kg of the studied fermented sea fennel in brine (both fresh and pasteurized) is 1,16. Looking at the contribution analysis, the packaging has the highest value in both cases as it was expected to be since their similarity. Regarding the agriculture contribution, it has higher value for borlotti beans which represent 0,15 kg CO_2 eq., comparing with 0,07 kg CO_2 eq. of sea fennel freshly harvested. Considering the end-of-life of packaging materials, the score for sea fennel preserve (0,00926 kg CO_2 eq.) is higher than the score for borlotti beans which correspond to 0,0004 kg CO_2 eq. Considering also that the production plant for borlotti beans use exclusively renewable energy, the compared values for the two products under study are in a certain way balanced. This means that changing the source of electricity and the packaging end-of-life, the environmental impact for producing sea fennel preserves can be reduced.

5.2.2 Scenario analysis for packaging

Sensitivity analysis has been performed considering the reduction of the packaging glass, being the most impacting input. Four different scenarios have been modelled: reducing packaging glass of about 10%, 20% and 30%. The results reported on the Figure 5-8 highlight that the CC scores do not differ significantly from each other. Further reduction on the thickness of glass container could not be plausible for the considered use of the packaging type because it will be too much fragile.

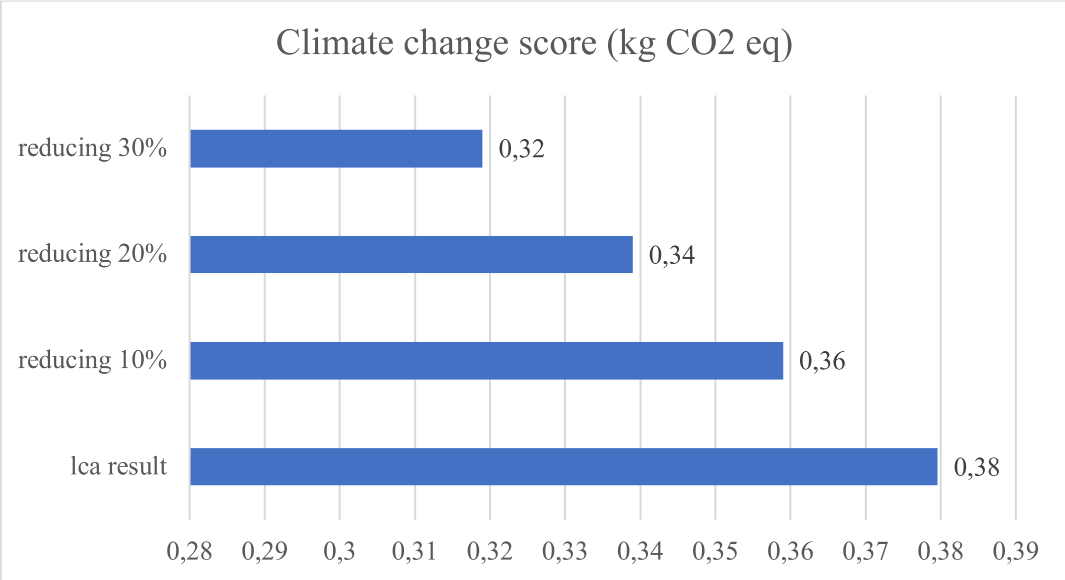

Figure 5-8 Comparison of climate change score between original results and alternative scenario results of reducing packaging glass.

5.2.3 Scenario analysis for use

Since the environmental impact for the studied fermented product are quite similar to each other, the sensitivity analysis has been performed including the use and assuming the refrigeration step. According with primary data collected during the questionnaire, fresh fermented sea fennel product should be stored in refrigerator where it lasts for 6 months. While, as is generally expected for acid foods, the considered pasteurized product doesn't require the refrigeration remaining stable for several months on the shelf and requiring refrigeration after the opening, condition in which the product lasts for about 1 week at most (U.S. Department of agriculture, 2024).

Including the refrigeration on performing the LCA, the results show that, from the environmental point of view, pasteurized fermented sea fennel product in less impacting than the fresh fermented product. The relative scores for climate change impact category are reported in the Figure 5-9.

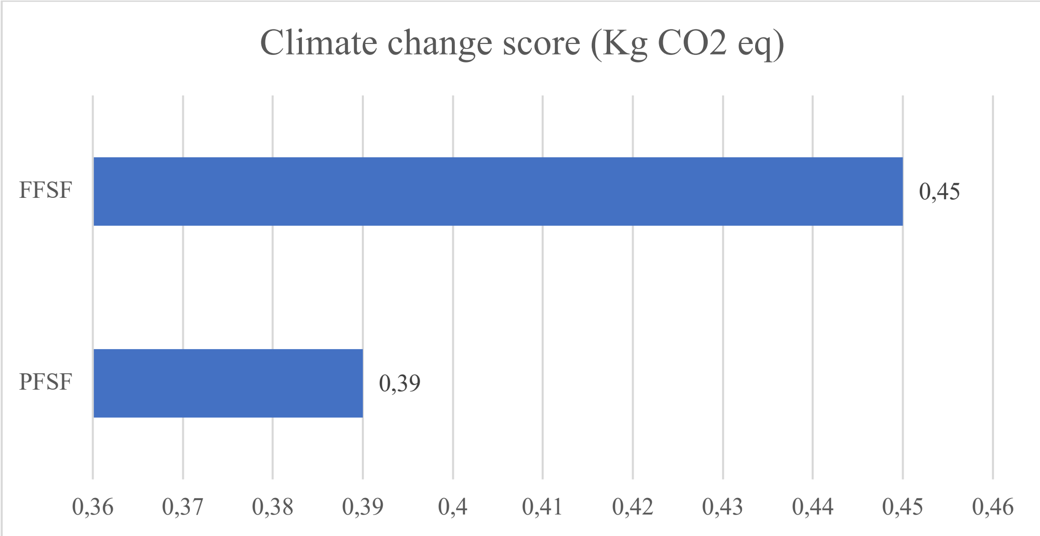

Figure 5-9 Comparison of climate change score between fresh fermented sea fennel and pasteurized fermented sea fennel product.

Further analysis has been performed by assuming the eventuality to throw away part of the product. Considering that the pasteurized product, once opened, lasts less than the fresh fermented one, further analysis were carried out assuming the possibility of having to throw away part of the because it had expired and was not consumed before the expiry date. The results reported in the Figure 5-10 shows the CC score resulting from the LCA analysis assuming 50%, 70% and 100% of wasted sea fennel to manage (the worst case has been considered, by assuming the municipal solid waste landfilling treatment). Results shows that for pasteurized product, even if it’s bought and thrown away entirely, from an environmental point of view is more sustainable than the compared fresh fermented product, which requiring longer refrigeration time shows higher environmental impact in terms of climate change.

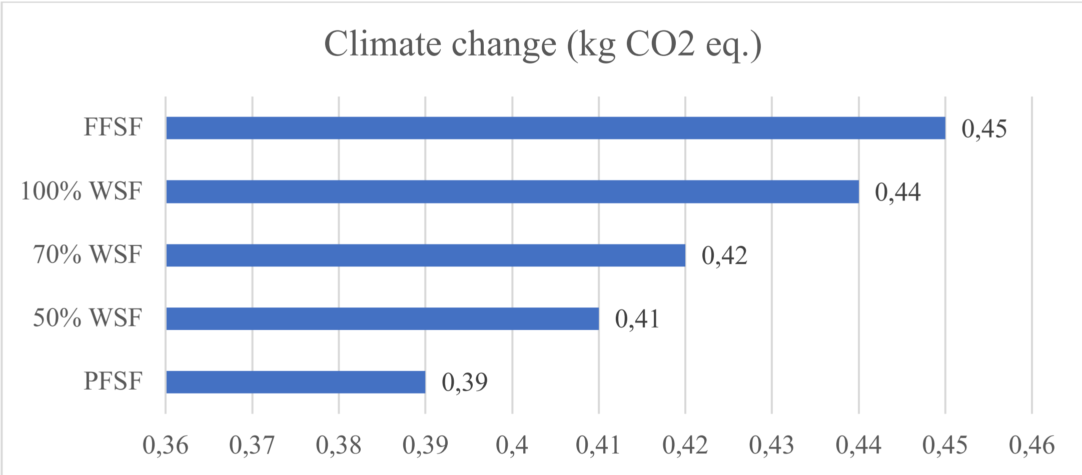

Figure 5-10 Comparison of climate change score between original results for both fermented product and alternative scenarios of wasted sea fennel.

CONCLUSIONS

This study explored the environmental impact of new products based on *Crithmum maritimum L.*, an adaptable and versatile halophyte, for the production of sustainable products. The study has been performed by Life Cycle Assessment, a method which allow the quantification of the environmental impact associated to a product for the entire life cycle.

The analysis has been performed for three new products: dried sea fennel spice, fresh fermented sea fennel in brine and pasteurized fermented sea fennel in brine. As expected, when the weight of the packaging is similar to the weight of the product inside, the results highlighted that glass packaging is the main contributor to the environmental footprint for the three products under study, suggesting that the best mitigation strategy could be the optimisation of packaging design and typology. Considering sea fennel spice product, the possibility to refill the same packaging with delivered spice through plastic bag of 1 kg significantly reduces the overall impact. Further analysis has been carried out making comparison between sea fennel spice results of climate change score with the score of analogue products like turmeric powder and chili powder, but the lack of detailed data in the literature do not allow a correct comparison. In fact, in general terms, it is more common to find LCA studies on crops, or single ingredients than processed products, like the ones analysed.

Considering fermented sea fennel products, the environmental impacts do not differ significantly in the gate-to-gate analysis. Further analysis has been carried out considering the use of the two fermented products. The comparison highlighted that from environmental point of view the fermented sea fennel product has lower environmental impact if pasteurized due to the lower refrigeration time needed. However, it important to consider the potential negative effects of additional thermal treatment on the quality of the final product such as colour changes and losses of volatiles.

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ACKNOWLEDGEMENTS/RINGRAZIAMENTI

Giunta al termine di questo ulteriore e meraviglioso traguardo, a distanza di due anni esatti da quello precedente ci tengo particolarmente a ringraziare (di nuovo) il mio relatore di tesi il Dott. Duca Daniele, per la professionalità, cordialità e disponibilità con cui mi ha accompagnato nella stesura di questo elaborato. Il suo supporto è stato prezioso.

Ringrazio la mia famiglia, mia madre e mio padre, per avermi supportato con fiducia nella scelta del proseguimento degli studi e avermi fornito un prezioso supporto economico. E nonna Maria che da sempre fa da sfondo alla quotidianità della mia vita.

Un ringraziamento a cuore aperto lo devo alle mie colleghe e amiche conosciute durante questo corso di laurea magistrale: Elena, Noemi, Angelica, Carla siete state delle persone così dolci e accoglienti! Sono eternamente grata per aver avuto l'opportunità di condividere questi due anni con voi. Le mie eccessive preoccupazioni e ansie si dissolvevano e la gioia raddoppiava grazie alla vostra presenza. Vi auguro di trovare, ovunque andiate un ambiente così caldo come quello che sapete così tanto creare, e un futuro colmo di successi.

Un ringraziamento speciale va al mio leale, amorevole, alleato compagno di vita: Michele, di anno in anno vediamo i nostri sogni realizzarsi e io mi sento profondamente fortunata ad averti nella mia vita. Con te ho imparato cosa significa amare ed essere amati, sentendo il cuore spezzarsi ma poi ricomporsi perché tu eri ancora lì e sentendo la serenità nell'animo, quella vera, e la gioia nel cuore, quella pura.