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Summary of Deliverable D8.3 – Sustainability Assessment of Sea Fennel Residue Extracts by LCA	Deliverable D8.3 explored the environmental profile of sea fennel residue valorization, transforming by-products such as stalks, leaves, and flowers into bioactive extracts and nutraceutical macrocapsules. Using the Life Cycle Assessment (LCA) method (ISO 14040/44), the study evaluated the impacts of lab-scale production and identified strategies to make future large-scale processes more sustainable. The results revealed that energy consumption was the dominant hotspot, with freeze-drying alone contributing over 65% of total impacts in categories such as climate change, acidification, and particulate matter. Producing 1 kg of macrocapsules was associated with about 6.04 kg CO_2-eq and a water use of 4.2 m^3, underlining the importance of energy-intensive steps. Other contributors included ethanol (as extraction solvent), which drove ecotoxicity and human toxicity, and sugar, which influenced eutrophication potential. In contrast, inputs such as calcium chloride, alginate, and water had minor impacts. A scenario analysis demonstrated the potential of renewable energy: switching from grid electricity to photovoltaic systems reduced impacts in most categories by more than 50%, with reductions of up to 76% for climate change and 82% for fossil resource use. However, it also highlighted trade-offs, such as an increase in mineral and metal depletion due to photovoltaic panel production. The findings emphasize that while sea fennel macrocapsules have strong potential as high-value nutraceuticals, eco-design is crucial. Priorities include optimizing freeze-drying, improving ethanol recovery, and integrating renewable energy sources. These improvements could transform what is currently an energy-intensive lab-scale process into a sustainable industrial pathway, consistent with EU circular economy goals and the Farm to Fork strategy.

Versioning and Contribution History

Version 1	Date	Modified by	Modification reason
v1.0	20/03/2023	Daniele Duca	First version
V2.0	27/03/2023	Daniele Duca	Final version

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1 Report on sustainability assessment of sea fennel residues extracts from data collected thanks to WP6 activities

1.1 Introduction

According to the Project WP6, by-products of the new crops will be valorized exploiting their "hidden value" as a potential source of bioactive extracts for the manufacturing of functional food ingredients/nutraceuticals and for the manufacturing of essential oils.

Pilot tests were carried out in WP6 for testing the exploitation of these innovative products. The life cycle assessment of a new sea fennel product (macrocapsules) was focused on the abovementioned trials, but no specific reference documents are currently present for these products. The LCA methodology was based on ISO 14040, ISO 14044 and scientific literature on similar products. A specific meeting was held with the partners involved to plan the data collection needed to calculate the environmental indicators by means of LCA.

1.2 Methodology

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 with different purposes, such as supporting strategic decisions to improve their environmental performance and communication). Due to the complexity of the topic, different technical documents produced at different levels are used to drive the analysis. At the highest level, the ISO standards of the 14000 family are devoted to environmental issues and include ISO 14040 and ISO 14044. These standards are the reference documents for carrying out 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. The assessment of the potential impact through LCA is based, according to ISO standards, on a four-step, iterative procedure (Figure 1).

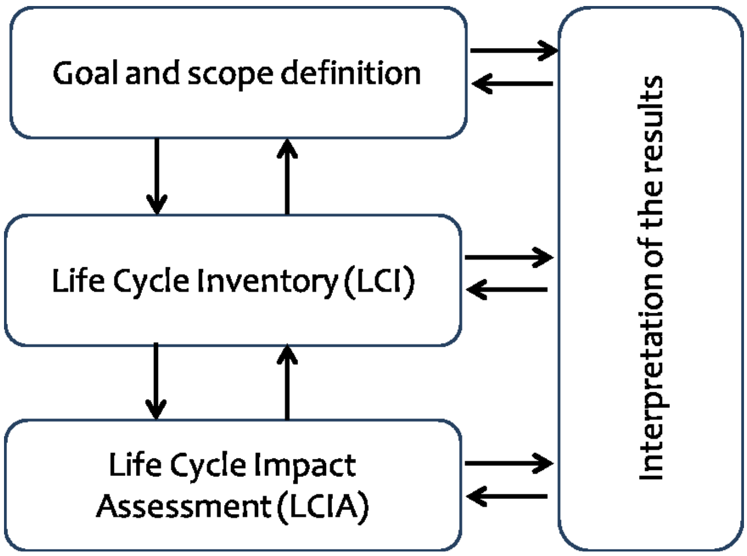

Fig. 1 – LCA framework according to ISO

The definition of goal and scope consists of the description of the product system under analysis, including the definition of system boundaries (mainly the phases of the supply chain included in the analysis with the related inputs and outputs) and the functional unit (FU), the unit to which the results of the study are referred. Other elements are the description of the reasons why the study is 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). Al the abovementioned assumptions are reported for transparency in this first step to avoid any misunderstanding on the LCA results and to improve the possibility to compare.

The life cycle inventory (LCI) is the step in which data collection is planned and realized. It consists in the definition and quantification of all input and output flows entering and exiting the product system under analysis. When available, primary data collected directly from the stakeholders of the supply chain 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 not available or their collection is not possible. Today LCA is widely used and internationally accepted LCA databases are now available for good secondary data. The result of LCI is the so-called inventory table where all inputs, outputs and emissions are reported with respect to the chosen FU.

The life cycle impact assessment (LCIA) step includes the characterization of the results, namely the quantification of the potential environmental impacts associated with resource 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 the four steps are considered consistent each other and in line with the goal and scope. If a step is not consistent this entails the iteration of the LCA until consistency is reached throughout the study.

Despite setting different pillars, the ISO standards are not focused on a specific product category, and additional documents are needed to limit the freedom of the practitioner and make the results more useful and comparable for similar products. For these reasons, other documents, in additional to the ISO standards, have been created by different bodies to be more specific for certain product categories. Unfortunately, no documents are currently available for macrocapsules, bioactive extracts or essential oils, but some research papers dealt with LCA applied to these products.

Among them, the following papers have been selected to provide guidance for the assessment:

- Techno-economic and environmental assessment of essential oil extraction from Oregano (Origanum vulgare) and Rosemary (Rosmarinus officinalis) in Colombia (Moncada et al., 2016)
- Environmental assessment of the essential oils produced from dragonhead (Dracocephalum moldavica L.) in conventional and organic farms with different irrigation rates (Maham et al., 2018)

- Environmental and economic assessment of food additive production from mushroom bio-residues (Pinto et al., 2022)

Based on the abovementioned documents, the following choices have been made for the LCA of extracts:

- Functional Unit: 1 kg of sea fennel macrocapsules
- System boundary: from cradle to the processing gate.
- The technical system do not include business travel of personnel, travel to and from work by personnel, research and development activity and buildings.

Based on the abovementioned documents and data constraints, the following aspects were considered in the LCA:

- Amounts of inputs of energy (fuels, electricity) and materials used for extraction
- Direct emissions from processing

Primary data have been collected from partners, and secondary data taken from LCA databases (Econinvent, 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 impact of sea fennel-based macrocapsule production for nutraceutical use. Given the significant bioactive compounds in sea fennel residues (stalks, leaves, flowers, etc.), this research sought to valorize this residual material into macrocapsules. Objectives included assessing the environmental impact of lab-scale production and identifying key environmental hotspots in the production and processing chains. This analysis contributes to a larger product eco-design effort to guide manufacturers toward more sustainable production practices prior to full-scale commercialization. The function of the system was to produce sea fennel-based macrocapsules. Therefore, the selected functional unit was 1 kg of sea fennel-based macrocapsules produced at lab scale in 2024.

The LCA follows a cradle-to-gate approach. The system boundary for microcapsule production, illustrated in Figure 2, details the capsule production process flow. The analysis excluded the drying of residue, transportation of residue and other input materials, and waste management due to data limitations. Foreground data were sourced from the UNIVPM team group and supplemented with background data from the Ecoinvent v.3.9.1 database (allocation, cut-off by classification processes). The processing data correspond to the year 2024.

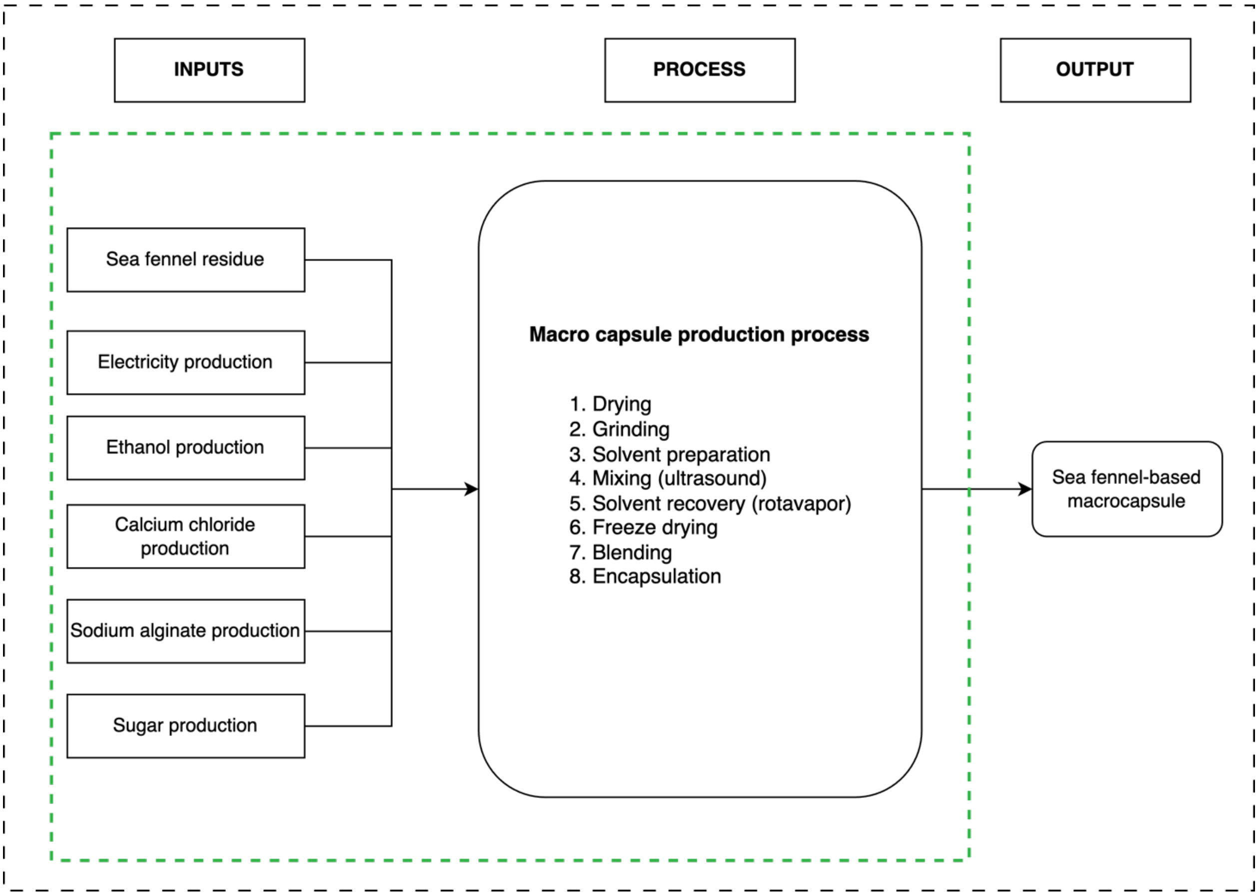

Fig. 2. The system boundary considered for the sea fennel microcapsule.

System description

Sea fennel residues (leaves, stalks, flowers, and stems) underwent pretreatment by oven-drying and grinding into a powder. This powder was mixed with an ethanol-water solvent (1:20 ratio) to create a 16% extract. Bioactive compounds were released from the extract using ultrasound for 30 minutes. The solvent was then evaporated from the extract via rotavapor at 40°C and recovered. The resulting product was freeze-dried for 20 hours to obtain a powder. To prepare macrocapsules, a homogenous mixture of 1.75% extract, 1.5% sodium alginate, and 2% sugar was created. Capsules were formed by dipping this mixture into a calcium chloride bath using a syringe, followed by washing to yield the final product. Primary data on the materials used were obtained from lab trials, while secondary data was used for electricity consumption (Di Clemente et al., 2025). Impact related to sodium alginate was also obtained from Nilsson et al. 2022.

Table 1. Inventory data for sea fennel-based macrocapsules, expressed per kg of product.

Parameter	Unit	Value	Data source
Input			
Sea fennel extract	g	32.4	Primary
Water	kg	2	Primary
Ethanol	g	15	Primary
Calcium chloride	g	27.8	Primary
Sodium Alginate	g	28.6	Primary
Sugar	g	38.1	Primary
Electricity (ultrasound)	kWh	0.1	Secondary
Electricity (rotavapor)	kWh	0.7	Secondary
Electricity (freeze-drying)	kWh	6	Secondary
Electricity (ultraturrax)	kWh	0.25	Secondary
Electricity (grinder)	kWh	0.64	Secondary
Output			
Sea fennel-based macrocapsule	kg	1	Primary

Life cycle impact assessment

We evaluated the impact assessment of this new product from sea fennel residues, 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 (RUF), and resource use, minerals and metals (RUM), 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 a sensitivity analysis to assess the influence of alternative energy source scenarios.

1.4 Main findings

The impact scores for the different impact categories based on the EF 3.1 method for sea fennel-based macrocapsules are provided in Table 2. The midpoint score for CC impact was determined to be 6.04 kg CO_2 eq./kg macrocapsule while water use was 4.21 m^3 depriv./kg macrocapsule.

Table 2. Midpoint impact scores for sea fennel-based macrocapsules, expressed per kg macrocapsule.

Impact category	Unit	Value
A	mol H^+ eq.	2.67E-02
CC	kg CO_2 eq.	6.04
ETF	CTUe	27.82
PM	disease inc.	1.36E-07
MEU	kg N eq.	4.24E-03
FEU	kg P eq.	1.29E-03
TEU	mol N eq.	5.07E-02
HTC	CTUh	2.85E-09
HTNC	CTUh	9.02E-08
IR	kBq U-235 eq.	0.75
LU	Pt	32.30
OD	kg CFC11 eq.	1.42E-07
POF	kg NMVOC eq.	1.86E-02
RUF	MJ	91.44
RUMM	kg Sb eq.	6.80E-05
WU	m^3 depriv.	4.21

(A: acidification, CC: climate change, EFT: ecotoxicity freshwater, PM: particulate matter, MEU: eutrophication, marine, FEU: eutrophication, freshwater, TEU: eutrophication, terrestrial, HTC: human toxicity cancer, HTNC: human toxicity non-cancer, IR: ionizing radiation, LU: land use, OD: ozone depletion, POF: photochemical ozone depletion, RUF: resource depletion, fossils, RUMM: resource depletion, mineral and metals, and WU: water use).

Fig. 3 presents a comprehensive hotspot analysis, revealing the relative contributions of various inputs and processes to the overall environmental impact of macrocapsule production across a range of impact categories. The analysis highlights the dominant contributors, depending on the specific environmental metric being assessed, to guide the development of relevant mitigation strategies. From the results obtained, energy consumption was the main contributor to the various impact categories. Electrical energy is essential for several processing steps, including grinding, freeze-drying, rotavapor operation, and ultrasound treatment. Notably, freeze-drying stood out as the most energy-intensive process, contributing over 65% to the total impact across most categories, except for ETF (50%). This disproportionate impact is directly attributable to the extended duration of the freeze-drying process, which can range from 20 to 30 hours. While freeze-drying is crucial for preserving heat-labile bioactive compounds present in sea fennel, its energy demands necessitate a critical evaluation of potential optimization strategies.

The lab-scale nature of this study implies that the production process has not yet been optimized for energy efficiency. As such, the observed energy consumption patterns likely represent a worst-case scenario. When transitioning to commercial-scale production, a concerted effort should be directed toward integrating sustainable energy sources, such as solar or wind power, to mitigate the environmental impacts of electricity consumption. Furthermore, investing in energy-efficient equipment and process optimization is paramount to reducing energy demands without compromising product quality.

Beyond energy, several material inputs also contribute to the overall environmental burden. Ethanol, used as a solvent in the extraction process, accounts for a significant portion of the impacts in categories such as ETF, HTC, and LU, contributing 28%, 15%, and 8%, respectively. This suggests that exploring alternative, less impactful solvents or optimizing ethanol recovery could yield substantial environmental benefits. Sugar, another key ingredient in the macrocapsule formulation, contributes approximately 10% to the total impact of Terrestrial Eutrophication (TEU). Conversely, inputs such as calcium chloride, sodium alginate, and water exhibit relatively minor contributions across the assessed impact categories.

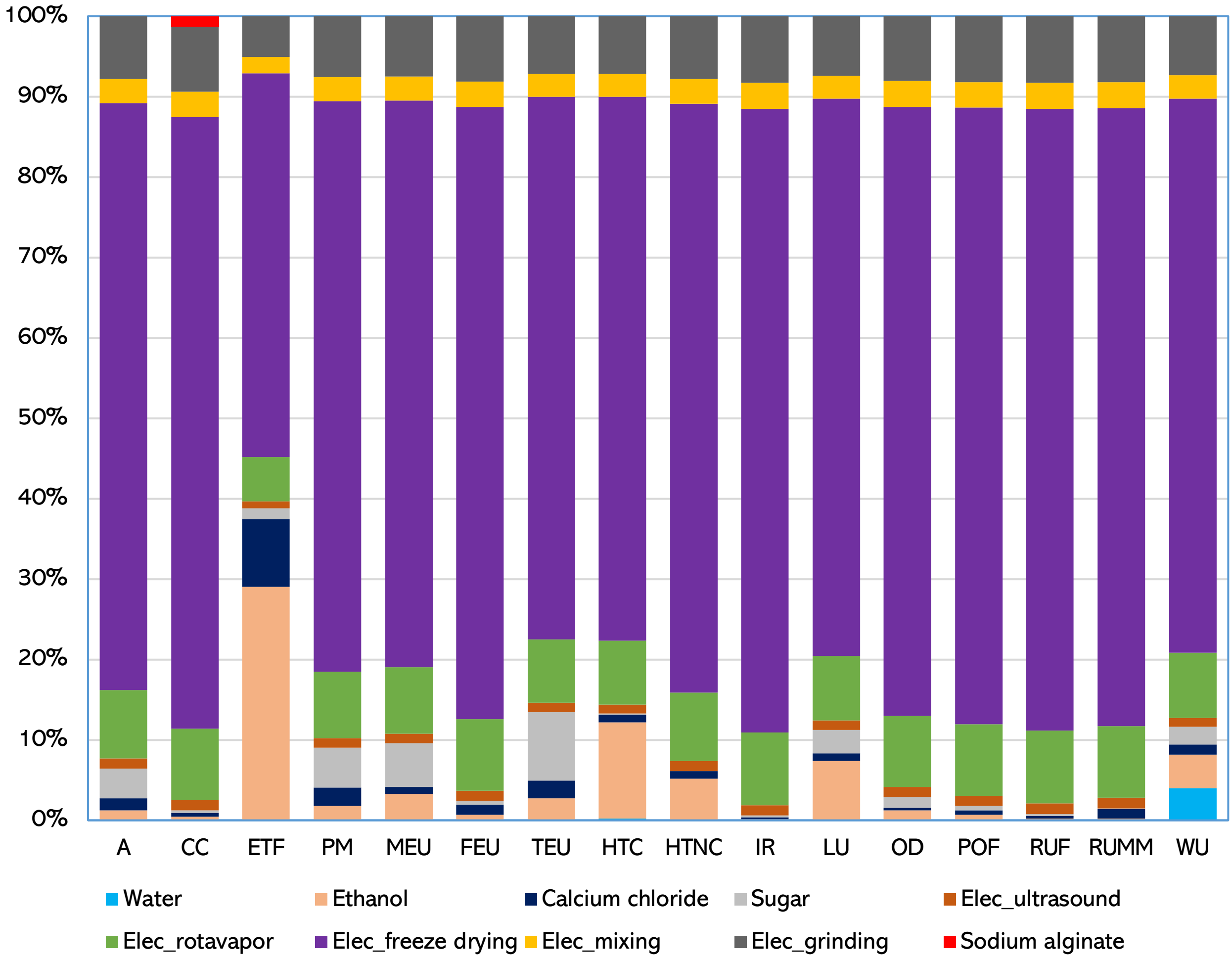

Fig. 3. Relative contribution of sea fennel-based microcapsule. (A: acidification, CC: climate change, EFT: ecotoxicity freshwater, PM: particulate matter, MEU: eutrophication, marine, FEU: eutrophication, freshwater, TEU: eutrophication, terrestrial, HTC: human toxicity cancer, HTNC: human toxicity non-cancer, IR: ionizing radiation, LU: land use, OD: ozone depletion, POF: photochemical ozone depletion, RUF: resource depletion, fossils, RUMM: resource depletion, mineral and metals, and WU: water use).

It is important to note that the specific environmental impacts associated with each input and process are contingent on factors such as the energy mix used for electricity generation, the sourcing and production methods of materials, and the efficiency of the equipment employed. Therefore, a comprehensive life cycle inventory encompassing these factors is essential for accurate impact assessment and targeted mitigation strategies.

Sensitivity analysis – Alternative energy source

Given that most of the impact of the macrocapsule was related to electrical energy consumption, there was a need to assess the effect of using an alternative energy source (renewable energy). To this end, a scenario analysis was conducted to assess the effect of switching the Italian grid electricity to photovoltaic energy.

Fig. 4 illustrates the potential environmental benefits of integrating photovoltaic (PV) energy into producing sea fennel-based macrocapsules. By substituting grid electricity with electricity generated from a 3 kWp building-integrated PV system, significant reductions were observed across most impact categories, exceeding 50% in many cases. The most notable reductions were achieved in IR (84%), RUF (82%), CC (76%), LU (73%), and POF (69%). However, it's important to note that this transition also led to a 13% increase in RUMM due to the upstream environmental impacts associated with PV technology, which requires high-purity materials and energy-intensive production processes.

While photovoltaic energy offers promising environmental benefits, several challenges must be considered for its effective implementation. The initial investment costs of installing a PV system can be a significant barrier for small- to medium-sized enterprises (Qamar et al., 2022). Although long-term energy cost savings can offset these costs, the initial investment may deter adoption without government subsidies or financial incentives. Furthermore, the seasonal variability in solar energy generation poses a significant challenge. This could necessitate supplementary energy from the grid during periods of low solar output, partially diminishing the overall environmental benefits.

Additionally, the disposal and recycling of end-of-life PV panels remain a significant environmental concern. 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 producing sea fennel-based macrocapsules offers a promising pathway toward greater sustainability.

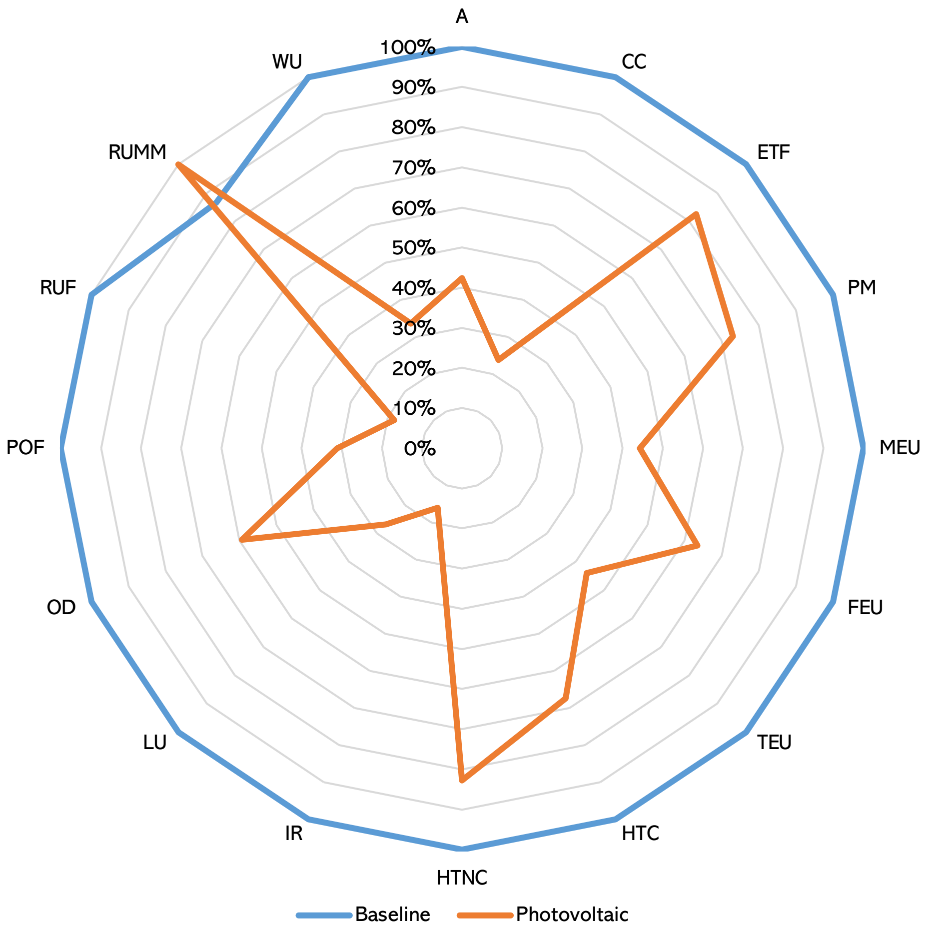

Fig. 4. Scenario analysis of energy source: comparison of baseline scenario (grid electricity) and alternative scenario (photovoltaic electricity). Blue line (baseline scenario); orange line (alternative scenario). (A: acidification, CC: climate change, EFT: ecotoxicity freshwater, PM: particulate matter, MEU: eutrophication, marine, FEU: eutrophication, freshwater, TEU: eutrophication, terrestrial, HTC: human toxicity cancer, HTNC: human toxicity non-cancer, IR: ionizing radiation, LU: land use, OD: ozone depletion, POF: photochemical ozone depletion, RUF: resource depletion, fossils, RUMM: resource depletion, mineral and metals, and WU: water use).

1.5 Conclusion

In conclusion, the potential environmental impacts of sea fennel-based macrocapsules at lab scale were assessed. As expected, the main contributor to the impacts was energy consumption, which underscores the importance of focusing on energy efficiency and material optimization to reduce the environmental footprint of sea fennel-based macrocapsule production at commercial scale. Future research should explore the feasibility of integrating renewable energy sources, optimizing solvent recovery, and investigating alternative materials or methods with lower environmental impacts. Additionally, a comparative life cycle assessment of different production scenarios, including varying scales and process technologies, could provide valuable insights for guiding manufacturers toward more sustainable practices.

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