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# Sustainability Assessment of Seaweed farming in Norway

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# List of acronyms

**FAO** Food and Agriculture Organization of the United Nations

**PEF** Product Environmental Footprint

**IMAT** Integrated Multi Trophic Aquaculture

**SETAC** Society of Environmental Toxicology and Chemistry

**ISO** International Organization for Standardization

**LCA** Life Cycle Assessment

**LCI** Life Cycle Inventory

**LCIA** Life Cycle Impact Assessment

**EPLCA** Environmental Platform on Life Cycle Assessment

**FU** Functional Unit

**AD** Abiotic Depletion

**AC** Acidification

**EU** Eutrophication

**GBP100** Global Warming Potential

**OLD** Ozone layer depletion

**HT** Human Toxicity

**FWET** Fresh aquatic ecotoxicity

**MET** Marine aquatic ecotoxicity

**TET** Terrestrial ecotoxicity

**PO** Photochemical oxidation

# Abstract

Global population growth is driving an increase in demand and consumption of natural resources, fueling growing environmental concerns. Therefore, finding alternative raw materials is necessary to meet both market demands and environmental needs.

Despite the fact that it is still a developing sector in Europe, implementing large-scale seaweed cultivation represents a valuable alternative for the production of various products such as food or energy. Several studies have shown both the contribution of their supply chain to local eutrophication mitigation and their ability to produce highly versatile low-carbon biomass. Resulting in a growing need to analyze the sustainability of this supply chain in order to ensure ongoing optimization and efficiency.

Within this context, the thesis focuses on evaluating the sustainability of the seaweed production of the Norwegian company PurSea. The environmental sustainability of the supply chain is assessed using a cradle-to-gate Life Cycle Assessment (LCA) to model the production system and calculate the impacts of the impact categories with both ReCiPe (midpoints and endpoints) and CML-IA baseline methods. CML-IA baseline method is used to obtain results comparable with literature, for the following impact categories: abiotic depletion (AD), global warming (GWP100), ozone layer depletion (OLD), human toxicity (HT), fresh aquatic ecotoxicity (FWET), marine ecotoxicity (MET), terrestrial ecotoxicity (TET), photochemical oxidation (PO), acidification (AC) and eutrophication (EU). ReCiPe method was used to achieve more deepened results, providing information with potential decision-making value to improve the company's environmental performance. Besides the categories in CML-IA, ReCiPe also calculates water consumption, mineral resource scarcity, fossil resource scarcity, fine particulate matter formation and land use.

The calculated impacts show an environmental footprint of 1700 kg $CO_2$ equivalent. The cultivation and processing (blanching, drying and freezing) have a higher contribution for all impact categories, mainly due to the choice of materials for infrastructures and machinery used. Waste management has a lower impact, except for marine eutrophication and ozone depletion. Finally, the hatchery has the smallest impact value. Results suggest the possibility of optimizing environmental performance using alternative processing systems, more environmentally friendly materials and, where possible, a greater focus on waste supply chain.

The literature comparison shows some discrepancies with respect to the results of other studies, due to some differences in production stages, the choice of methods in Ecoinvent and of inputs included in the analysis. Lastly, the impact of seaweed farming was compared with the aquaculture sector: seaweed has a similar impact of farmed fish (about 1900 kg $CO_2$ equivalent) however, it has a higher value compared to the shellfish production (about 9 kg $CO_2$ equivalent).

# 1. Introduction

## 1.1 Seaweed and their relevance

Seaweed are photosynthetic aquatic organisms including different and countless species of marine plants and algae which inhabit several water bodies as lakes, rivers or oceans. Santos et al., (2015) estimated that about 25000 – 30000 species of seaweed can even grow in extreme environmental conditions. In order to do so, these species have developed the production of various secondary metabolites as defence strategy.

Seaweeds are eukaryotic organisms taxonomically classified (even if they belong to three unrelated lineages) based on their pigmentation: green (Chlorophyta), red (Rodophyta) and brown (Ochorophyta) (Costa et al., 2021; Taelman et al., 2015). The species *Saccarina latissima* belongs to the brown class. Furthermore, seaweed can be distinguished based on their size: from microscopic algae, living suspended in the water column and providing food for marine food chains, to medium and large, who live in underwater forests (National Ocean Service, 2021).

In aquatic ecosystems, seaweed play mainly two essential roles:

1. seaweed convert solar energy into biomass, i.e. chemical energy, and therefore, they are at the base of the food web of most aquatic ecosystems;
2. seaweed provide various ecosystem services and environmental benefits such as carbon capture and sequestration, eutrophication mitigation, ocean acidification amelioration, habitat provision and shoreline protection (FAO, 2021).

Therefore, according to Buschmann et al. (2017), seaweed can be a valuable tool, in nutrient cycling, for the mitigation of water nutrient loading and also for avoid the increase the greenhouse emissions, through the improvement of carbon fixation. From this perspective, seaweed could be a potential solution to the current environmental concerns. In addition, seaweed cultivation could help the reduction of land use and related environmental burdens (Wageningen, 2016). For these reasons, seaweed could become a significant input for the economy and society.

Seaweed biomass is suitable for a variety of applications as they are used different format (e.g. dried, fresh, salted, liquid extract), which could either sold for direct consumption or could be processed into other products (Buschmann et al., 2017).

The application of seaweeds stretches in multiple sectors: as cosmeceuticals (Balboa et all, 2015) for creams and lotions, as nutraceuticals (Himaya et al., 2015), as pharmaceuticals (Anis et al., 2017), as ingredients for food and feed (Fleurenze, 2016) because seaweedsare full of vitamins, fibre and minerals, as raw materials for specially polysaccharides (Bixler et al., 2011), as textiles, as biofertilizer, as biofuel and for wastewater treatment and integrated aquaculture (McHugh, 2003; FAO, 2018).

## 1.2 Seaweed farming developments

Since ancient times, seaweed were used by humans, thanks to their various benefits and different applications (Buschmann et al., 2017). However, only 1700 years ago was found the first written record of the human use of seaweed in China (Yank et al., 2017).

Initially, seaweed were harvested from the coasts and utilized as food or feed for domestic purposes, afterwards seaweed were applied in the medical field. Nowadays, seaweed are exploited in many industrial sectors such as cosmetic, bioenergetic and pharmaceutical sector (Buschmann et all, 2017).

Since the 1950s, seaweed industries globalization determined a large-scale seaweed cultivation growth, defining the current farming models and since 2015, the 94% of annual seaweed biomass utilized globally derives from cultivation sites (Hafting et al., 2015).

In the last years, the interest in seaweed grown, due to the increasing necessity of alternative resources to produce food, feed, fuel, cosmetics and pharmaceuticals (Campbell et al., 2019). Moreover, different processing options were developed to obtain functional products with higher values for different application, with the aim of minimizing environmental impacts and waste of the process (Hafting et al., 2015).

This is only an introduction about the growing role of seaweed in the international economy, specifically in the global aquaculture, where in 2019 seaweed cultivation (wet weight) represented 30% of the world aquaculture production (120 million tonnes) (FAO, 2021).

### 1.2.1 Social and economic aspects

According to Rosamond et al., (2021), since the 2000s the worldwide macroalgae production volume doubled, representing the third aquaculture sector with an annual increase in production growth rate of 5.7% in the production of macroalgae (NETALGAE). In 2017 algae covered 43% of total aquaculture output (live-weight) (FAO, 2019).

In the past 20 years, the appreciation for seaweed increased (Rosamond et al., 2021) thanks to their potential uses. As the demand outstripped the available supplies, the number of countries that commercially harvest seaweeds increased. At present, 35 countries cultivate seaweed as an economic resource, including China, Japan, Korea, parts of South Africa, Indonesia, Philippines, Europe (FAO Fishstat, 2014). From 2000 to 2017 the global production increased threefold from 10 Mt of cultured seaweed to more than 32 Mt.

It should be considered that about 97.4% of the global seaweed production comes from Asia, mainly China and Indonesia, while the Americas and Europe contributed respectively 1,4% and 0,8% (FAO, 2021).

From the economic perspective, since 2003 the estimated total annual value of the seaweed industry is of $5,5-6 billion USD, where $5 billion USD come from the use as food products for human consumption. On the quantities of biomass produced by industry, 7,5-8 millions wet weight tonnes seaweed, both naturally grown and cultivated, are used in different ways by industry (FAO, 2003). Worldwide, the average selling price of algae is $250 USD per tonne. According to Porse et al., (2017) this is a too high price that could limit net revenues and innovation incentives for this sector. In Europe, seaweed production is still much smaller than in Asia: the countries in which it is most developed are France, Ireland and Norway (Barbier et al., 2019). It is due an older oriental cultural tradition in which seaweed were well known for human food purpose (Costa et al., 2021), while Europe considered seaweed for purposes other than direct human consumption like e.g., products for agricultures or pharmaceutical (Ngo et al., 2011).

According to Buschmann et al. (2017), seaweed farming has a positive social impact contributing to the well-being of society. In industrialized societies, the macro-algae sector can generate jobs by considering the different levels at which the sector is involved: starting with the processing and distribution of services, up to the last level where there is a direct employment in the production company.

A FAO research project (2003) analyzed several case studies and results showed that the development of the seaweed cultivation sector could lead to an improvement of social conditions in the area. In fact, this sector was proved to be very profitable for several coastal communities: various studies showed that an algae producer net earns five times more than a plots farmer in one hectare (Valderrama et al., 2015). In addition, it is an activity that favours family dimension (on a small scale) over larger farms (plantation), generating more employment than other aquaculture farms.

Furthermore, the cultivation of seaweed in these marginal areas guarantees benefits for society as it discourages overfishing; in fact, many of these communities base their economic and social system on coastal fishing, which is heavily exploited. The introduction of seaweed makes it possible to increase the resources available to these people.

International agencies have already exploited the potential of this activity by promoting the cultivation of algae in Indonesia and neighboring countries, in order to try to improve the population living conditions. The result was a substantial improvement in the living standards of people who could improve their educational level, have an improved nutrition, or increase their purchasing power over material goods (FAO, 2003).

# 2. Scope and structure of the thesis

## 2.1 Scope of the thesis

The topic for this thesis was selected taking into account the socio-economic and environmental context that has been developing since the 2000s.

In 2022, the United Nations Department of Economic and Social Affairs issued a statement on world population growth, estimating to reach 8.5 billion people in 2030 and 9.7 billion in 2050. This demographic growth carries a twofold problem: the supply of human resources and the protection of the environment. Agriculture and intensive farming are likely to lead to an increase in solid and water degradation, climate change, competition between animal feed and human food industry and also a reduction in the availability of biofuels (Costa et al., 2021).

Over the last decade, several studies and research tried to address these concerns and identified macroalgae as a first solution to the problems highlighted above. Seaweed represent a valuable primary resource with different sectors of application and with relatively low environmental impacts. Their cultivation allows one to obtain valid primary resources behaving like nutrient capture agents (Thomas et al., 2020). In this sector, research is growing more and more to be able to optimize the seaweed production to meet the demands of the market, producing the least possible impact.

This thesis fits into this context: the main goal is the assessment of the environmental sustainability of seaweed cultivation in Europe: the Norwegian company "PurSea" was selected as a case study.

The assessment, aimed at identifying the environmental impacts of the production system, the processes that most contribute to the impact and explore different hypotheses to reduce the impact.

The Life Cycle Assessment (LCA) method was used to calculate the contribution of the environmental loads generated along the life cycle of a product. A cradle-to-gate approach model of the production chain was created in order to:

- identify the most critical processes, in term of environmental impact, thus providing to a company suggestions for improving the sustainability of their products;
- compare the results with literature regarding both seaweed farming and other aquaculture branches, in order to rank the sustainability of seaweed farming.

## 2.2 Thesis structure

After the first chapter, in which the seaweed importance from an environmental and socio-economic point of view was introduced, the aims of the thesis were defined.

The third chapter describes the background of the case study. The most widely used cultivation systems and typical processes of seaweed after harvesting are set out in the chapter, with a specific paragraph for the *Saccharina latissima* species. Then, some possible impacts from seaweed cultivation are examined, and finally, is showed an overview about the seaweed farming Norwegian context, with the description of PurSea company, i.e. the case study.

Once the case study was introduced, the method of study and research, the literature review, the concept of life cycle assessment and the tools used, are described in the fourth chapter. Within this chapter, the specific objectives and methods applied to the case study are defined, and data provided for the analysis are described.

Chapter five describes the results from the analysis of environmental impacts calculated, while in the sixth chapter, the results are interpreted and the comparison with other literature results is made. Suggestions are also provided to reduce the major impacts identified reading the results.

Finally, chapter seven shows the conclusions of the thesis, calling for an increase in LCA research to improve the efficiency of seaweed production systems.

# 3. Background

## 3.1 Seaweed farming systems

Seaweed can be cultivated at different scales, which determinate the application of different methods. The scale ranges from intensive production based on on-lands tanks, to extensive open-sea cultures which are the most commercially successful (Sahoo et al., 2005).

Considering that the farming system may differ based on the country in which is applied, worldwide the most common systems are the open-sea methods, which apply either fixed or floating lines techniques, as one can see in Figure 1.

The fixed off-bottom method uses lines (of monofilament nylon) or ropes (polypropylene) stretched between wooden stakes, usually 1 meter apart. Poles are pounded into the substrate. On the lines, are tied small pieces of seaweed which usually reach in six or eight weeks 10 times their original size and they can be harvested.

In the floating lines method (typically a square timber frame), seaweed are suspended on a floating construction or raft, around 50 cm below the sea surface. Sometimes, plastic bottle could be used as floatation devices. This method is suitable where marine currents are weak or the deep of the sea prevents from fixing the bottles lines. The floating line method advantage is the possibility of moving the lines to a better position or removing them from the water in case of bad weather. Instead, the off-bottom line system allows the farmer to have easier access to seaweed (McHugh et al., 2003) and it is advantageous for its cheapness, simplicity, easy installation and maintenance.

In Europe, it is preferred to use the floating lines method, although the fixed off-bottom method is also widely used due to the high labor costs and exposed coastline (Taelmann et al., 2015).

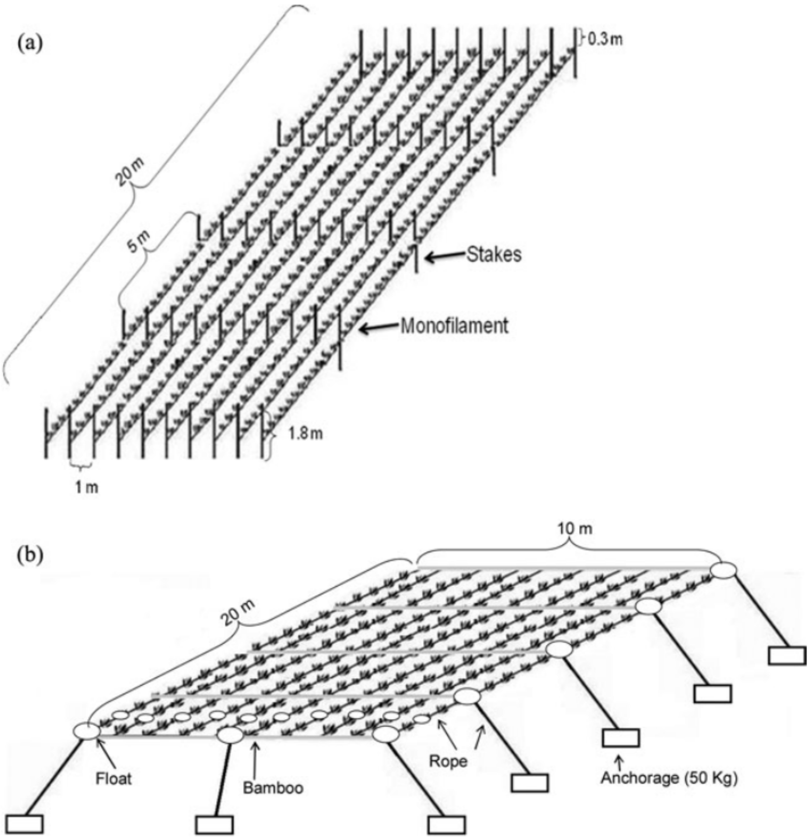

*Figure 1: Culture technique a) fixed off-bottom method; b) floating lines system. The dimensions are only as example (Valderrama et al., 2015)*

As far as the land-based systems are concerned, in the last 20 years a new concept of combined farming is growing. Intensive cultivation requires a high nutrient uptake which led an increase in the production of wastewater with high levels of organic load causing possible downstream eutrophication issues (Costa et al., 2021). Due to this issue, a different approach for the cultivation of macroalgae and seaweed-based products, was developed (Barbier et al., 2019) combining intensive cultivations with the production of fish and organic extractive feeders to implement the removal of excessive inorganic nutrients allowing the reduction of aquaculture wastes (Troell et al., 2009). This system, initially used in Portugal, is called

Integrated Multi Trophic Aquaculture (IMTA) and is applied on in-land, in a controlled environment (Buschmann et al., 2017).

Each cultivation system still depends on the life cycle of seaweed specie: some grown through a vegetatively cycle, others involve a separate reproductive cycle with alternation of generations. This influences the choice of the cultivation system and the production costs.

In vegetative cultivation, pieces of seaweed are used as seedstock and placed in a favourable environment for the growth. The harvesting can be carried out in two ways: by removing the whole plant or by retaining a part for further cultivation.

Seaweeds such as the Laminariae, that require a sexual reproduction aquaculture, cannot grow by cuttings taken from mature ones, but they demand the union between a sporophyte and a gametophyte through a sexual phase. The mature sporophyte releases gametophyte, that once it is fertile, releases sperm and eggs which join to form embryonic sporophytes. These develop into the large sporophytes that are harvested. During farming of these species, e.g. *Saccharina latissima* o *Undaria pinnatifida*, is difficult to control the sexual phase and these transitions is usually carried out in land-based facilities, with high control on the living conditions (in a small twine in a nursery). Productions based on the latter seaweed have high costs which could only be mitigated if seaweeds are sold as food (FAO, 2003).

In Northern Europe, the production is mainly limited to two period of the year where nutrients and light are sufficient to allow the growth; these periods are spring and beginning of autumn. In addition to this limitation, another problem is presented by the crop quality, caused by high levels of fouling during summer months (Andersen et al., 2017). Usually, in late spring to early summer the algae mature and are harvested, although it still depends on the type of species, the environmental conditions and the season.

### 3.1.1 *S. latissima* cultivation and product processing

*Saccharina latissima* grows through sexual reproduction and, in aquaculture, S. *latissma* needs an artificial substrate on which growing. Therefore, hatchery is necessary and it takes place in land facilities in specific laboratory. This phase includes two sub-phases: a first phase of spores preparation and a subsequent sowing.

The objective of the first step is to obtain a concentrated solution of spores. The parent specimen is an seaweed blade that is cleaned, cut and left to incubate from 6 to 10 weeks in specific tanks, in filtered seawater. To the sample, is guaranteed continuous artificial lighting, water recirculation and temperature control.

Once the spores were obtained, sowing is carried out. The spores are left in incubation for depositing on ropes. The spores are implanted in the ropes that are wrapped around plastic pipes. After 3-5 weeks, the spores are transferred into the sea.

When seaweed have grown enough, they are moved to sea and cultivation begins. The ropes with seaweed are wrapped around the longlines. Usually, the cultivation system at sea consists in the floating lines, that is a system of buoys and floating longlines. The buoyancy is due to the presence of anchor buoys that are connected to an anchor with ropes, chains and shackles.

Once seaweed matured, they are collected with special machinery on boats and stored in bags for collection. Usually, in Northern Europe as in Norway, the harvest is around the end of spring and early summer, when seaweed are about 1 or 2 meters long.

After collection, S. *latissima*, such as other seaweeds, needs processing for stabilizing its wet biomass and for long-term storing. Thus, seaweed are brought to the processing plant where they are firstly drying, reducing the material volume and weight, hence minimising packaging, storage and transportation cost. Usually hot air-drying systems are used, expending considerable energy. Then, freezing is used for storage of seaweed and it is the most widely used method.

For both process, different machines are used, such as conveyors, drum dryers, fans for heating and plate freezers, which are energy-intensive. As the result, drying and freezing lower the economical and environmental sustainability of the processing chain (Barbier et al., 2019).

Seaweed could be mixed with salt and then packaged to be stored and sold to other producers.

## 3.2 Norway interests

In Europe, the interest in seaweed led to establish an industry network to support European seaweed industry and to encourage stakeholder’s cooperation. This network is called

"Netalgae". In addition, this network aims to create the best-practice guidelines for the regulation, administration and management of seaweed resources.

In this scenario, Norway became the world second largest exporter of seaweed (Stévant et al., 2017), and its annual production is still a growing. Furthermore, Norwegian seaweed harvesting system is one of the best management systems worldwide, although conflicts still persist between seaweed trawling industry and other coastal zone users (Stévant et al., 2017).

In Norway (as in the rest of Europe) *S. latissima* is the species on which the production effort was concentrated, due to its potential for producing high amount of biomass. The 96% of the total Norwegian production is represented by *S. latissima*, although licences were granted for other species such as *Alaria esclutenta*.

Norway morphological characteristics and its geographic position are important factors for the seaweed economy. The complex Norway coastline extends for over 100 000 km and is characterized by fjords, islands and skerries ensuring suitable condition for aquaculture. Also, cold temperate waters of the Northeast Atlantic favour the growth of various species with significant commercial value.

After the successful trials in Scotland, Germany, France, and Ireland, in 2005, the farming of kelps started in Norway. Nowadays, different stakeholders, both privately owners and researchers, are trying to develop new farming strategies for reducing the need for technical maintenance byenhacing the automatization. The purpose of companies is to continually improve the efficiency with the aim of increasing product quality by maximising the use of biomass.

In 2014, public authorities granted the first commercial license for seaweed farming cultivation. Between 2014 and 2016, seaweed cultivations licensed areas more than tripled, however, seaweed cultivation sites were still scarce and not evenly distribute along the coast, mainly concentrating in the mid and north part of the country. For areas more than 10 ha, license holders are required to document that their production is environmentally sustainable (Barbier et al., 2019). Furthermore, there were few sites IMTA where seaweed cultivation sites are closed to fish farm; most IMTA sites were not built for fish and seaweed co-cultures, but they were initially constructed only for fish farming and implemented later.

A further increase in demand may lead to site large scale seaweed production away the Norwegian continental shelf, to avoid possible conflicts with other uses and increase production.

To conclude, seaweed farming cultivation is growing, contributing to Norwegian bioeconomy. It is essential to foster cooperation between public authorities, industries and research institutes in order to develop a legal framework that facilitate the creation of a sustainable algae-based industry (Stévant et al., 2017).

## 3.3 Seaweed farming impacts

According to Campbell et al. (2019) the construction of a seaweed culture plant requires a prior knowledge of the potential impact on the ecosystem, in order to minimize impacts in water systems. The implications of seaweed production should be taken into account in the selection of suitable sites and farming methods. The environmental factors, that can be altered by the presence of a farm, are different and mainly include light absorption, nutrients and carbon, additional noise, artificial materials and alien species. Those factors could lead to the significant changes, not necessarily negative.

In aquatic ecosystems, the quantity and quality of light are essential factors which influence the structure of seaweed communities. Since crops must be placed on surface water to obtain an adequate level of active photosynthetic radiation, the seaweed layer may shade the underlying habitats causing an alteration of the living conditions of phytoplankton, benthos and communities of marine phanerogams, that would suffer a greater pressure on pasture and competition for resources. It is therefore essential to take this factor into account when locating large-scale projects, although it is highly unlikely that individual crop sites could have a significant impact.

Another consequence of large-scale farms is an excessive removal of nutrients, such as nitrogen, from aquatic ecosystems, which may affect biodiversity. According to Campbell et al., (2019), it was shown that this phenomenon is highly unlikely in European cultivations as it has a marginally significant impact, while in China cases of nutrient depletion were observed.

Another possible anthropogenic impact on the environment is the increase in ship traffic and machinery for site activities that could lead to behavioral changes in animal communities. The impact is assumed to be proportional to the size of the crop, however, the location of the site is always considered in relation to sensitive characteristics of the area.

Ongoing research are trying to estimate the problem of trapping megafauna species. The extension of the risk is still unknown, but it is certain that large-scale plants have greater impacts than small ones. Authorities require to know the location in order to avoid important areas for foraging, breeding and migrating marine fauna. In addition, the same materials can be accidentally lost at sea contributing to pollution. Even though, it is always assumed that the plants are operated responsibly and that a good maintenance minimize the impact.

One problem associated with algae farming is the risk of introduction of exotic species which could become invasive.

Lastly, an important effect of macroalgae culture is carbon absorption. It was studied that seaweed aquaculture is able to remove large quantities of carbon, while providing alternative food and energy resources characterized by low carbon emissions (Costa et al., 2021).

The above impacts are common to farms around the world. However, in the European context, some regulations and recommendations about seaweed-related activity already exist (Barbier et al., 2019). The European contest includes the member states of the European Union and also Norway, which through the European Economic Area (EEA) Agreement, participates in a series of EU programmes and agencies about the market, education, research, environment which includes guidelines on seaweed activity (Europa.eu).

In conclusion, environmental legislation and policies dictate a set of common farm management principles, to guarantee the sustainability of seaweed farming. Below, just some aspects that are already controlled, are listed: protection of the most sensitive environmental sites, the control and restrictions on the breeding of alien species (according to the Alien Species Regulation 1143/2014 EU), the recommendation not to use fertilizers and, finally, the need to use properly maintained (Barbieri et al., 2019).

## 3.4 PurSea seaweed farming

The Norwegian company PurSea provided information and data, representing the case study of the thesis.

The company is located in Rødøy on the Helgeland coast (Figure 2). The region is located south of the article polar circle and is world famous for its pristine and nutrient-rich waters. The region characteristics favour the sustainable development of seaweed.

The processing plant, shown in Figure 3, is developing to accommodate new production lines to diversify product categories. In fact, the company's objectives are to become a protagonist of the seaweed cultivation industry, respecting the values of environmental and social sustainability.

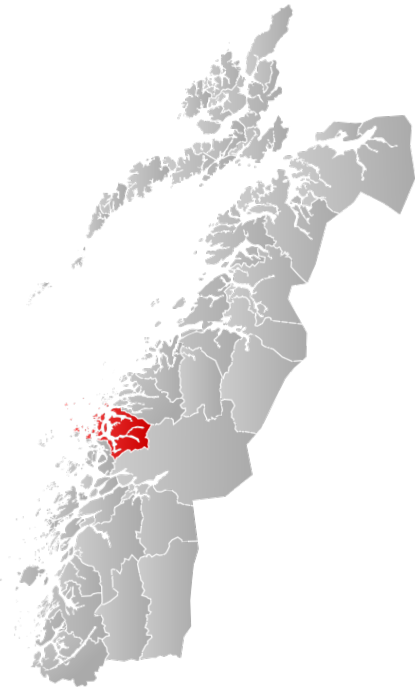

*Figure 3: Municipality of Rødøy, in Norway*

*Figure 3: Example of PurSea production facilities, located on Selvøvik, in Norway (PurSea.no)*

As mentioned in the introduction, seaweed production can play an important role in the social and economic improvement of the region in which it is located. PurSea is in line with this vision and intends to contribute to the development of the region by creating new jobs and promoting culture for this activity.

The company is part of the Norwegian Seaweed Association (NSA) which deals with the promotion of international standards, enhancing the positive impact of seaweed and promoting common interests or problems to public administrations.

PurSea is mainly concerned with the cultivation of seaweed, their processing and subsequent sale to other economic actors. The production chain is characterized by 4 phases: hatchery, cultivation, harvesting and processing. Processing includes blanching, drying and freezing. For each phase, infrastructure and machinery are required, and represents the inventory inputs for analysis.

Annually, the company produces 10 tonnes of *S. latissima* in fresh weight.

# 4. Methodology

## 4.1 Literature review

To contextualize the following work, it is necessary to explore the scientific landscape regarding LCA studies on seaweed cultivation.

The bibliographic research was carried out using the online databases of: Sciences Direct, ResearchGate and Frontier. The main keywords used for the research were "seaweed farming", "macroalgae", "aquaculture", "environmental impacts", "risks", "life cycle assessment". Papers published from 2012 to 2021 were selected.

The literature review indicated that there are still a few LCA studies on seaweed production, despite properties of macroalgae and their uses were studied for more than 20 years (Naylor et al., 2021). In 2015, Valderrama (Valderrama et al., 2015) wrote an article stating the beneficial impacts of algae cultivation activities for marginal coastal societies, in eastern countries. Naylor et al., in 2021 and Buschmann et al., in 2017 explored potential uses and retrospectives of macroalgae, by focusing, for example, on biofuel, without forgetting, however, concerns about the possible impacts or problems that this activity can generate. In response to this last point, a review of the potential and generated environmental impacts by this industry was written by (Campbell et al., in 2018).

However, farming systems are still poorly studied using a life cycle approach, probably due to the emerging seaweed sector in Europe. The main studies focus on the analysis of the sustainability of algae production for energy purposes, such as biofuel production. This is the case of Seghetta et al., (2017) paper, whose research is focused on the comparison of different scenarios for biogas production, methane content and different ingredients for fish feed. In the same context, the article written by (Aitken et al., 2014), examines the environmental impacts of seaweed cultivation and transformation into bioethanol and biogas. Other LCA studies have been carried out in terms of exergia, showing that the cultivation of macroalgae is more efficient than the one of terrestrial plants (Tealmann et al., 2015).

Drifting from research based on the energy role of seaweed, Orischot et al., (2017) studied the production chain from a strictly environmental perspective, investigating two production models suggesting being careful in the design of cultivation systems. Among the most recent articles, there is the Thomas et al., (2020), which analysed the environmental impacts of a pilot facility in Sweden, comparing some alternatives for both sowing methods and preservation.

In conclusion, this thesis can contribute to enrich the scientific panorama in this field, as the application of LCA to seaweed production is still limited, compared with other aquafarming typologies.

## 4.2 Life Cycle Assessment

The Life cycle assessment (LCA) is a standardized method to quantify and evaluate the environmental and energy loads, as well as the potential impacts of a product, process or service, throughout its life cycle. The perspective of this method should be based on the entire life cycle of a product, starting by analyse the extraction of raw materials and ending with the disposal procedures (Roy et al., 2008; Nieuwlaar, 2016). It is, therefore, a holistic approach to assess environmental impacts, as stated by Fava et al., (2013), and guarantees an overall vision of the interaction between environment, resources and human health, facilitating the identification of trade-off. Moreover, it is a relative method based on a functional unit. The analysis focus on environmental aspects and impacts, while economic and social aspects are not considered. The key feature of an LCA study is its transparency, that ensures understanding and correct interpretation of data. Finally, the last principle on which this methodology is based on is the need to always take preferential decisions on a scientific basis (ISO, 2006).

Currently LCA is a standardized tool from the International Organization of Standardization in the series: ISO 14040 describes principles and framework, while ISO 14044 defines requisites and provides guidelines to perform the analysis.

The structure of an LCA is defined by the ISO, as one can see from Figure 4, it is divided into four phases: goal and scope definition, inventory analysis, impact assessment and interpretation. LCA is an interactive technique, as each phase uses the results from the other phases. It means that the analysis does not proceed linearly, from one phase to another, but there is a continuous interaction between all four phases. The interaction ensures completeness and consistency of results.

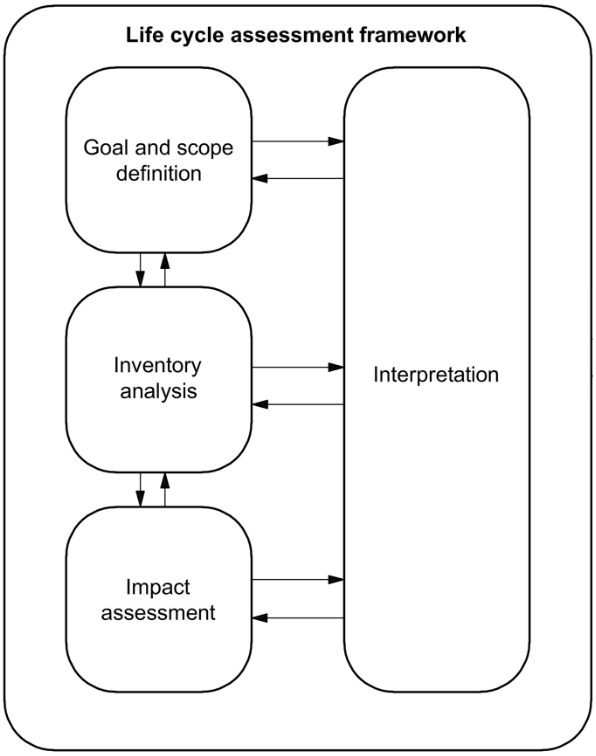

*Figure 4: Life cycle assessment framework phases (ISO, 2006)*

LCA was introduced in the 1960s, but according to Kloppfer et al., (1997) only around the ’90, a generally accepted method was developed to harmonize the different systems of environmental impact analysis. In 1993 the Society of Environmental Toxicology and Chemistry (SETAC) established the first guidelines for life cycle assessment; however, this method is still undergoing further development (Nieuwlaar, 2016). In the late 1990s, life cycle analysis was identified as the best tool for the development of efficient and integrated environmental policies (Berkhout et al., 1997). Whereas more recently, according to Roy et al., (2008), LCA is becoming a very important tool for industries and authorities.

As Jacquemin et al., (2012) and the ISO (2006) define, LCA can be used to address different needs, as:

- assessing the environmental impacts of individual products,
- comparing production systems or replaceable processes,
- comparing alternative models of the same system,
- identifying critical points in a production chain or life cycle,
- identifying environmental indicators,
- investigating the environmental performance of a product, to optimize its performance and provide information for environmental declarations or certifications (marketing)
- informing tool for strategic planning or product design government or industrial decision-makers.

### 4.2.1 Goal and scope definition

The goal and scope definition phase is crucial while performing an LCA, because the analysis is based on the statements and assumptions chosen during this phase (Roy et al., 2008).

According to ISO 2006 guidelines, at this stage are defined: the reasons why the study purpose, its application, the assumptions, the expected product and the public to address the results. Moreover, the functional unit and the system boundaries are chosen.

The functional unit (FU) represents of the reference unit to with which the inventory data and the results are related. It is the unit that allows one to normalize the data, making them comparable with other products. It is also the unit used to measure the performance of the input and output of the product. The FU can be a physical unit (such as mass) or it could be related to the potential use of the product (such as nutritional values) (Roy et al., 2008; Nieuwlaar, 2016).

LCA is performed based on a model, that uses inputs and outputs to describe the production systems analysed. Inputs and outputs are modelled within the system boundaries, which includes the most significant phases of product or system life cycle. Not all phases can be included, those with a negligible impact may be omitted. The exclusion of a phase or process from borders is called cut-off and must be justified (Nieuwlaar, 2016).

In general, the chosen system boundaries depend on the choices made during the scope definition phase, and should take into account flows, unit processes and different phases of the life cycle (ISO, 2006). There are different types of boundaries such as: cradle to gate, gate to gate, cradle to grave and cradle to cradle. Each type is differentiated by the choice of life cycle stages included, as one can see in Figure 5.

For the thesis a cradle-to-gate analysis was carried out. It represents a partial life cycle that begins with the extraction of raw materials used, continues with processing and production and, it ends at the gate of the manufacturing facility.

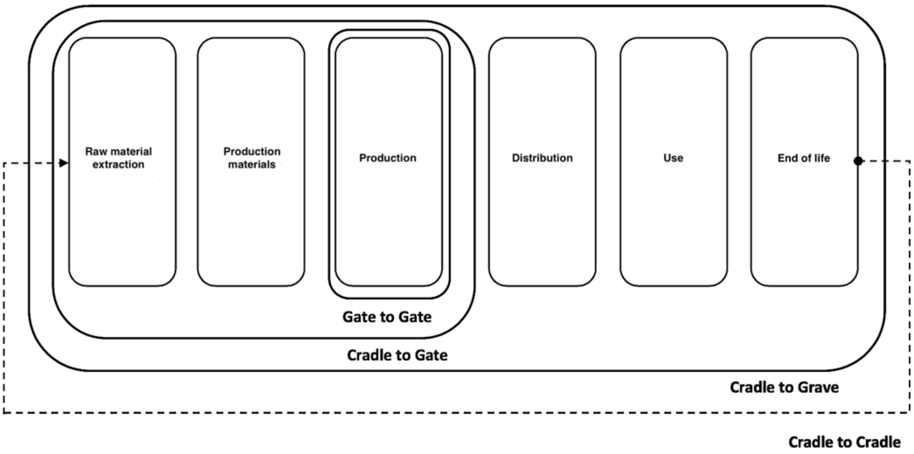

*Figure 5: Different types of system boundaries*

### 4.2.2 Inventory analysis

In the second phase of the LCA, data are collected and processed. This is the most laborious and interactive phase since the data is requested directly from suppliers or customers.

Some information on materials processing or transportation are already stored in a LCA database, while specific data must be properly requested.

If there is a lack of information, it can be compensated in several ways: making assumptions, using expert estimates or undertaking a bibliographical search for missing data. The data provided increases the knowledge of the system and may lead to the modification of some choices in the first phase of LCA.

Afterwards, the life cycle inventory (LCI) is created, and it includes all inputs such as energy, raw materials, natural resources and outputs such as products, co-products and emissions. All processes in the inventory are usually expressed in a flow chart, which is a graphical representation of the flows and materials that describes the system of the product.

In addition, data undergoes calculation during this phase. First, it is necessary to carry out a validation of the collected data. The data are normalized in relation to the chosen FU. If co-products are present, it may also be necessary to make an allocation or distribute the inputs, outputs and unit processes between product and co-products. (ISO, 2006; Nieuwlaar, 2016; Roy et al., 2008).

### 4.2.3 Impact assessment

In the third phase of LCA, inventory data are converted into possible indicators of the potential environmental impact that damages environmental, animal and plant health.

The Life Cycle Impact Assessment (LCIA) phase identifies and quantifies the potential environmental impacts of inputs and outputs into the LCI. They are associated with specific environmental impact categories and their indicators.

There are several impact categories defined at two levels, as shown in Figure 6: midpoint and endpoint. According to Jolliet et al., (2004) the midpoint level choice allows one to assess the impact placed in an intermediate area between the results of the inventory and the final damage. The other method uses endpoints that are three and, according to Jolliet et al., (2004), are: human health, ecological health and resource depletion. The two methods are complementary as the midpoint approach is closer to environmental flows, while the endpoint approach provides information on environmental relevance (Hauschild et al., 2012 and Huijbregts et al.,2015).

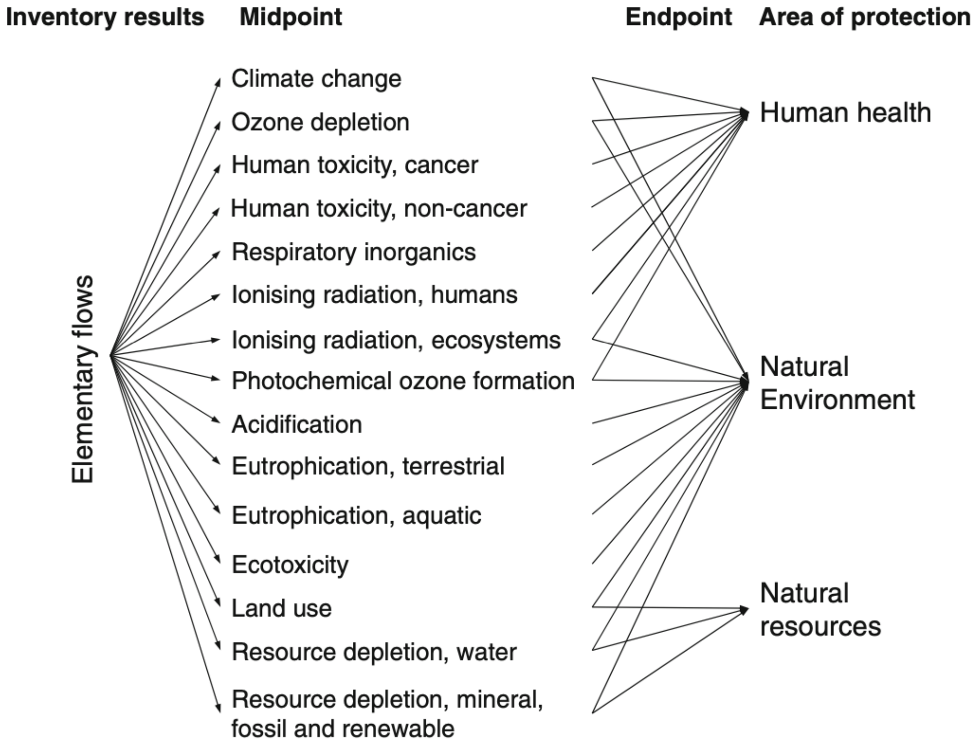

*Figure 6: Framework of LCI characterization linking elementary flows, from the inventory results to indicator results, at midpoint and endpoint level for 15 midpoint impact categories and 3 areas of protection (Hauschild et al., 2012)*

The impact categories are various and their choice introduces subjectivity in the phase of impact analysis. For this reason, it is essential to ensure the transparency of every decision. The impact categories at midpoint level are disparate and are characterized by: impact scale at local or global level, compounds that potentially produce them, and finally the characterization factor and its calculation. Table 1 describes the most widely used midpoint impact categories, according to the Scientific Applications International Corporation (2006).

The impact categories to be included in LCIA should be consistent with the goal and scope. In addition, midpoint or endpoint analysis can be performed by selecting the method used. For example, impact processing methods like CML 2002 exploit the midpoint level, systems like EPS work at the endpoint level, while the ReCiPe method tries to combine the two levels (Hauschild et al., 2012).

*Table 1: Table of most widely used midpoint impact categories according to Scientific Applications International Corporation*

| **Impact Category** | **Scale** | **Examples of LCI Data** | **Common Possible Characterization Factor** | **Description of Characterization Factor** |
|---|---|---|---|---|
| Global Warming | Global | Carbon Dioxide (CO2) Nitrogen Dioxide (NO2) Methane (CH4)<br>Chlorofluorocarbons (CFCs)<br>Hydrochlorofluorocarbons (HCFCs)<br>Methyl Bromide (CH3Br) | Global Warming Potential | Converts LCI data to carbon dioxide (CO2) equivalents<br>Note: global warming potentials can be 50, 100, or 500 year potentials. |
| Stratospheric Ozone Depletion | Global | Chlorofluorocarbons (CFCs)<br>Hydrochlorofluorocarbons (HCFCs)<br>Halons<br>Methyl Bromide (CH3Br) | Ozone Depleting Potential | Converts LCI data to trichlorofluoromethane (CFC-11) equivalents. |
| Acidification | Regional<br>Local | Sulfur Oxides (SOx) Nitrogen Oxides (NOx) Hydrochloric Acid (HCL) Hydroflouric Acid (HF) Ammonia (NH4) | Acidification Potential | Converts LCI data to hydrogen (H+) ion equivalents. |
| Eutrophication | Local | Phosphate (PO4)<br>Nitrogen Oxide (NO)<br>Nitrogen Dioxide (NO2) Nitrates Ammonia (NH4) | Eutrophication Potential | Converts LCI data to phosphate (PO4) equivalents. |
| Photochemical Smog | Local | Non-methane hydrocarbon (NMHC) | Photochemical Oxident Creation Potential | Converts LCI data to ethane (C2H6) equivalents. |
| Terrestrial Toxicity | Local | Toxic chemicals with a reported lethal concentration to rodents | LC50 | Converts LC50 data to equivalents; uses multi- media modeling, exposure pathways. |
| Aquatic Toxicity | Local | Toxic chemicals with a reported lethal concentration to fish | LC50 | Converts LC50 data to equivalents; uses multi- media modeling, exposure pathways. |
| Human Health | Global<br>Regional<br>Local | Total releases to air, water, and soil. | LC50 | Converts LC50 data to equivalents; uses multi- media modeling, exposure pathways. |
| Resource Depletion | Global<br>Regional<br>Local | Quantity of minerals used Quantity of fossil fuels used | Resource Depletion Potential | Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve. |
| Land Use | Global<br>Regional<br>Local | Quantity disposed of in a landfill or other land modifications | Land Availability | Converts mass of solid waste into volume using an estimated density. |
| Water Use | Regional<br>Local | Water used or consumed | Water Shortage Potential | Converts LCI data to a ratio of quantity of water used versus quantity of resource left in reserve. |

LCIA development, in according to the Environmental Platform on Life Cycle Assessment (EPLCA), takes place in four phases:

1. Classification: after impact categories, category indicators and characterization models are selected, each input and output from LCI are associated with its own impact category; for each LCI data there may be several impact categories.
2. Characterization: for each input and output (for the respective impact category), the magnitude of impacts is calculated; the contributions belonging to the same impact categories are added together, to obtain the impact indicator (e.g. GWP) through the characterization factor.
3. Normalization: LCIA results are normalized in a dimensionless value to facilitate comparison of the different categories results. This is an optional phase.
4. Grouping and weighting: this operation facilitates the subsequent interpretation of the analysis. The normalized data are multiplied with weighting factors, to observe the relative importance for each phase of the life cycle. This is an optional phase too.

Figure 7 outlines the LCIA stages.

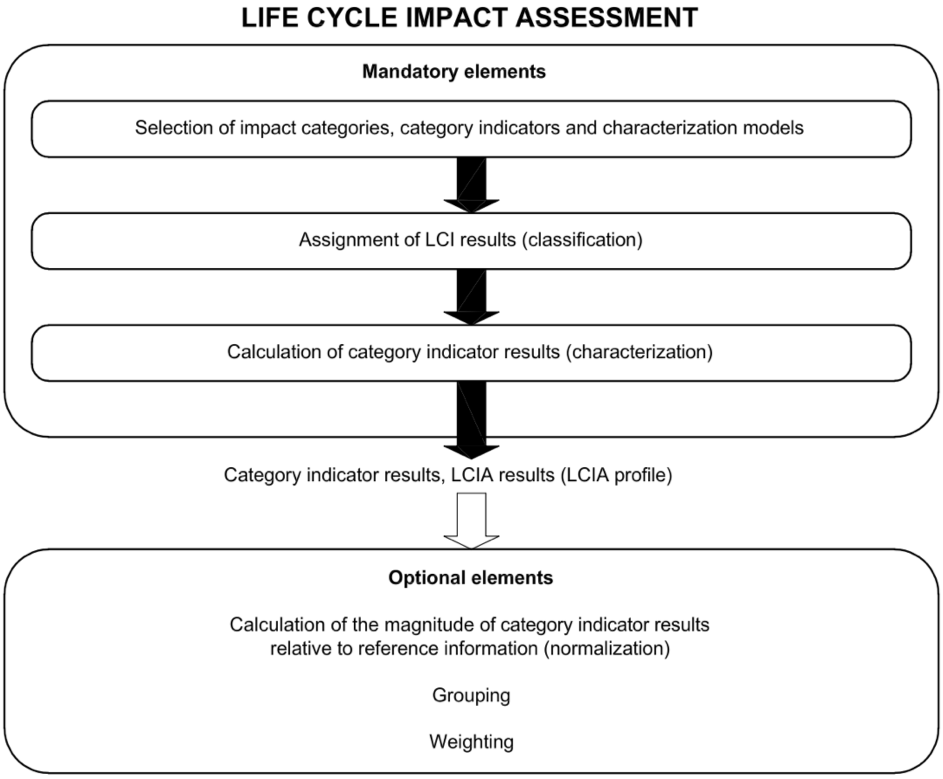

*Figure 7: Phases of LCIA (ISO, 2006)*

### 4.2.4 Interpretation

The last step of the LCA framework is the interpretation of the results. It represents a LCA phases, introduced by ISO 14043 (Klopffer et al., 1997), that affects data and the entire LCA procedure.

The data obtained in the previous steps are subject to a quality assessment. The results are examined on their consistency related with the objectives initially defined and their completeness. At this stage a sensitivity analysis could also carried out from the data, to see how much the data can be affected by variations of analytical methods or other arbitrary choices (ISO, 2006).

The ISO standard defines LCA as a decision support tool, so it is important to verify that the results are correct, clear, justified and easily understandable. They are also the basis for making recommendations and improvements to the processes involved. The critical analysis presupposed at this stage allows one to identify even the most significant issues, such as the phase with the most impactful process, the categories of impact with the greatest contribution or anomalous values to be examined (Roy, 2008).

Finally, Nieuwlaar (2016) argued that the possibility of accurately answering the question "which process has the best environmental performance" is unlikely. This is because LCA results are affected by inaccuracies and uncertainties. The latter are highlighted in the interpretation phase and are mainly related to: assumptions made in the first phase, a percentage of uncertainty of the evaluation calculations and the subjectivity introduced in the choice of impact categories in the LCIA phase.

## 4.3 SimaPro Software

The current landscape of tools and methods for LCA processing presents several choices. The available softwares are SimaPro, Gabi, OpenLCA, and Umberto, and are all widely used in the world. Each tool differs from the other in the completeness of the included database, the ease of use and the way they assess the impact. Some differences depending on the software, can generate very different results. As a result, the choice of software can influence the outcome and interpretation of the LCA (Silvia et al., 2017).

These tools have several methods for calculating impacts that should lead to different results. The most widely used impact analysis methods are CML 2000, ReCiPe 2008 and EPS 2000. Their main difference concerns the level of analysis (midpoint or endpoint) and clarity of interpretation (Hauschild et al., 2012). Despite the obvious differences between methods and tools, guidelines do not yet exist to suggest the most appropriate choice (PRè-sustainability, 2016).

SimaPro is a software for modeling and evaluating production systems. It was conceived in 1990 by PRè Sustainability and, it is used and distributed worldwide (PRè-sustainability, 2012). The system contains a diverse number of standard methods for environmental assessment.

The software is easy to use (Silvia et al., 2017) because, thanks to the interface, the user can model the production system and easily view the results. Once the results are obtained, they are processed by hand, often using Excel.

Two databases are already included within SimaPro: a life cycle unit process database (Ecoinvent) and a database for impact assessment applicable to each chosen method. The information in the databases has a scientific basis to ensure transparent analysis (SimaPro.com).

Finally, the software is complemented by a calculator to convert input values into impacts, depending on system modeling (Herrmann et al., 2014).

In terms of its performance, several studies have shown that SimaPro is more conservative than GaBi (Silvia et al., 2017).

Simapro can be widely applied for the creation of sustainability reports, product certifications, environmental declarations, optimization of production systems, definition of performance indicators and in general as support to decision-making processes.

### 4.3.1 Ecoinvent database

Within SimaPro, the Ecoinvent database is installed by default, but other LCI databases such as AGRIBALYSE, Agri-footprint can be used.

Ecoinvent was founded in 2000 by a project launched by several Swiss LCA institutes, leading to the creation of an LCI archive that reflects production systems and the Swiss, European and global market.

It consists of a harmonized database comprising more than 18 000 datasets that model processes and activities. The system data consists of the value of the impacts caused by emissions, exploitation of resources and waste produced associated with each process.

The archive covers a complex range of sectors, such as transport, building materials, energy, chemicals, paper, agriculture and waste treatment. Each activity in the database refers to a geographical location (Europe, Europe without Switzerland, Global etc.). This provides a more relevant figure for each product, depending on the area of interest.

The quality of Ecovinvent lies in its traceability and transparency. In fact, each process or product has its own updated and detailed documentation in EcoSpold format (Frischknecht at al., 2005) and the user can consult online the annual reports on database changes (Ecoinvent.org).

Finally, Ecoinvent is compatible with several LCIA methods such as ReCiPe or CML.

### 4.3.2 CML

The CML method (Centrum voor Milieukunde Leiden) was developed by the University of Leiden (Netherlands) in 2001. CML-IA database contains characterization factor for LCIA.

Within the CML-IA there are two approaches: baseline (the most used) and not baseline (Bach et al., 2016). Both can be used, but the baseline method is used for the thesis.

The method uses 11 midpoint impact categories, as Table 2 shows, and it is widely recognized, reproducible and well documented (Koesling et al.,2020).

*Table 2: List of impact categories for CML baseline method*

| Impact Category | Unit |
|---|---|
| Abiotic depletion | kg Sb eq |
| Abiotic depletion (fossil fuel) | MJ |
| Global warming (GWB100a) | kg CO2 eq |
| Ozone layer depletion (ODP) | kg CFC-11 eq |
| Human toxicity | kg 1,4-DB eq |

| | |
|---|---|
| Fresh water acquatic ecotoxicity | kg 1,4-DB eq |
| Marin acquatic ecotoxicity | kg 1,4-DB eq |
| Terrestrial ecotoxicity | kg 1,4-DB eq |
| Photochemical oxidation | kg C2H4 eq |
| Acidification | kg SO2 eq |
| Eutrophication | kg PO4-- eq |

CML is also in line with the recommendations proposed by the international life cycle data system. These characteristics make it a widely used, robust method with a high coverage of important materials (Lieberei et al., 2016), used in environmental analyses in aquaculture.

### 4.3.3 ReCiPe

ReCiPe is an environmental impact assessment method in SimaPro, introduced in 2008 by the Dutch National Institute for Public Health in collaboration with the Environment (RIVM), Radboud University Nijmegen, Norwegian University of Science and Technology, and PRé-sustainability (PRè-sustainability.org). Currently, the template that is used is the ReCiPe update 2016.

This method converts LCI values into impact indicators at two levels: midpoint and endpoint. Exactly, 18 midpoints and 3 endpoints are used (Huijbregts et al., 2016).

The midpoint impact categories with the corresponding indicators are indicated in Table 3. The midpoint impact categories are assigned to three protection areas representing the three endpoint impact categories.

Table 3 shows the areas: human health, ecosystem quality and resource scarcity. Each endpoint is evaluated with a different unit: human health is measured by the DAYLY, the life expectancy that a person loses (or is disabled) due to illness or accident. The unit of measurement of the quality of the ecosystem consists in the loss of local species over time, while the dollar measures the scarcity of resources and indicates the costs for the future extraction of fossil or mineral resources (Huijbregts et al., 2016).

Table 3: Midpoints and Endpoints according to ReCiPe 2016 (Huijbregts et al., 2016).

Midpoint

| Impact Category | Unit |
|---|---|
| climate change | kg CO2 to air |
| ozone depletion | kg CFC-11 to air |
| ionizing radiation | kBq Co-60 to air |
| fine particulate matter formation | kg PM2.5 to air |
| Photochemical oxidant formation: ecosystem quality | kg NOx to air |
| Photochemical oxidant formation: human health | kg NOx to air |
| terrestrial acidification | kg SO2 to air |
| freshwater eutrophication | kg P to fresh water |
| human toxicity: cancerogenic | kg 1,4-DCB to urban air |
| human toxicity: non-cancerogenic | kg 1,4-DCB to urban air |
| terrestrial ecotoxicity | kg 1,4- DCB to industrial soil |
| freshwater ecotoxicity | kg 1,4-DCB to fresh |
| marine ecotoxicity | kg 1,4-DCB to marine water |
| land use | m2·yr annual crop land |
| water use | m3 water consumed |
| mineral resource scarcity | kg Cu |
| fossil resource scarcity | kg oil |

Endpoint

| Endpoint | Unit | Area of protection |
|---|---|---|
| damage to human health | year | human health |
| damage to ecosystem quality | species·yr | natural environment |
| damage to resource availability | dollar | resource scarcity |

Finally, with this method, impacts can be analyzed from three perspectives: the individualistic, hierarchist and egalitarian perspective. In the thesis the egalitarian perspective was used. It represents the most precautionary view as it takes into account all possible impact paths and considers a longer time frame (Huijbregts et al., 2016)

## 4.4 Application to case study

### 4.4.1 Goal and scope definition

As previously introduced, the purpose of the LCA study is to analyse the environmental sustainability of the seaweed production chain.

This LCA study is an exploratory analysis. It means that its intention is to explore seaweed production to know which are its effects on the environment, and the extent of the impacts produced. Therefore, the results will not be used to request an environmental declaration or a quality certificate, but the data can be used to help the company improve its environmental performance. However, LCA studies are often necessary to obtain environmental certifications in order to be more competitive on market. The LCA results need to be always related to similar studies results, to be meaningful. For this reason, the European Union is trying to develop the Product Environmental Footprint (PEF) that is a multi-criterion measure to assess the environmental performance of a product or service, during its life cycle. PEFs are used to compare related products and are produced following the PEF Category Rules, which are guidelines for obtaining comparable footprints. As with ISO 14044, PEFs present impact categories, called Environmental Footprint Category (Manfredi et al., 2012). To date, however, the development of the PEF for the aquaculture sector doesn’t exist yet.

However, in the company’s interests, the study could highlight the hotspots, i.e. critical processes from the environmental footprint point of view. Once identified, it is possible to hypothesise alternatives with better performance both economically and environmentally. The analysis can therefore represent a source of new information available to the company for its more efficient and sustainable development.

Once the purpose of the LCA was expressed, it is essential to identify the functional unit, that is the reference unit of measurement of inputs, outputs and impacts. For seaweed can be used different FU such as 1 ha of sea surface cultivation, 1 tonne of protein or 1 mg of dry weight (Seghetta et al., 2018). The choice of the most suitable functional unit is dictated by the function it should have and its usefulness for possible comparisons (Guinée, 2002).

In this thesis, 1 tonne of algae *S. latissima,* expressed in fresh weight was taken as the Functional Unit.

Figure 8 shows the system boundaries, i.e. the limits within the analysis extends, indicated with a dotted line: the system includes incubation, grow-out phase, harvesting and processing processes.

Therefore, a cradle-to-gate LCA was performed. Steps such as distribution, consumption or product termination were not considered. The system boundaries include all processes, energy and fuel flows, materials and emissions that participate in product formation.

Finally, the lifetime of the facilities was estimated to be about 30 years, while for consumable inputs it was considered an about one year of life.

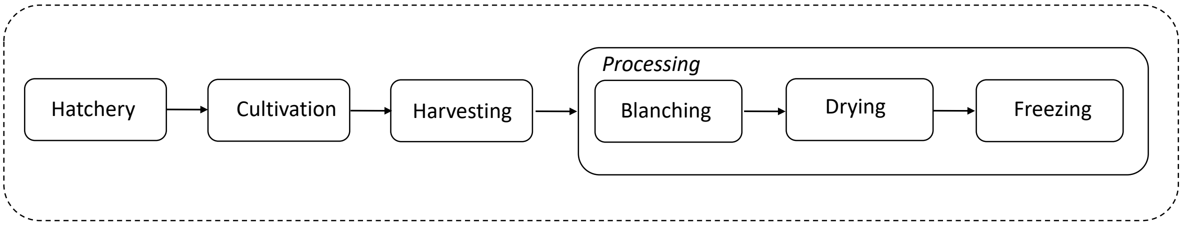

*Figure 8: System boundaries cradle-to-gate for seaweed production*

## 4.4.2 Inventory and assumptions

Figure 9 shows the process flowchart where squares indicate the processes, circles indicate materials and energy resources, and arrows indicate the flows.

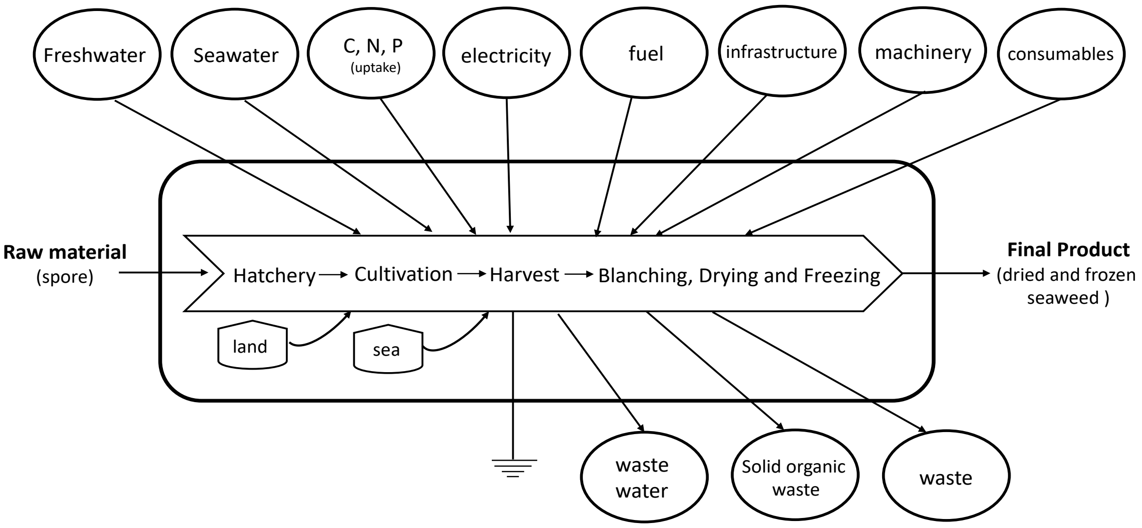

*Figure 9: Process flowchart of seaweed production*

The graphic representation facilitates the understanding of the flows into and out of the system boundaries, and schematizes the components involved in the production of the product.

The processes flowchart is built from information shared by the company. Based on the flowchart, the inventory was constructed.

Table 4 represents the case study inventory and consists of infrastructure inputs, energy consumptions, consumable materials and machinery used for the seaweed production. The complete inventory table is presented in Appendix A.

*Table 4: Life Cycle Inventory for 1 tonne of seaweed fresh weight*

| Item | Typology | Value to FU | Unit |
|---|---|---|---|
| *Hatchery* | | | |
| Tanks | Infrastructure | 3,3333 | kg |
| Pumps | Infrastructure | 0,1500 | kg |
| Pumping station | Infrastructure | 0,1333 | m3 |
| Pipes | Infrastructure | 10,8100 | kg |
| Lighting system | Infrastructure | 0,0667 | kg |
| Seawater filters | Infrastructure | 0,0600 | kg |
| Microscope | Infrastructure | 0,0200 | kg |
| Scale | Infrastructure | 0,0100 | kg |
| Working gears | Infrastructure | 1,0000 | kg |
| Ropes 2mm | Consumable | 11,3726 | kg |
| Ropes 8mm | Consumable | 45,4903 | kg |
| Seawater | Consumable | 100,0000 | m3 |
| Freshwater | Consumable | 1,0000 | m3 |
| Electricity for filtration | Consumable | 3000,000 | kWh |
| *Cultivation* | | | |
| Anchor | Infrastructure | 100,0000 | kg |
| Anchoring buoy | Infrastructure | 5,3533 | kg |
| Buoy | Infrastructure | 3,0000 | kg |
| Chain | Infrastructure | 25,2000 | kg |
| Anchoring rope | Infrastructure | 0,1066 | kg |
| Longline | Consumables | 1,3042 | kg |
| Shakcles | Infrastructure | 0,2500 | kg |
| Vessel | Infrastructure | 1,6667 | kg |
| General consumables | Consumables | 1,0000 | kg |
| Fuel for cultivation | Consumable | 25,5000 | kg |
| *Harvest* | | | |
| Vessel | Infrastructure | 1,6667 | kg |
| Machinery on vessel | Infrastructure | 20,0000 | kg |

| | | | |
|---|---|---|---|
| Harvest bags | consumables | 2,0000 | kg |
| Fuel for harvesting | consumable | 10,2000 | kg |
| Fuel for preprosessing | Consumable | 2,9750 | kg |
| Fuel for transporting | Consumable | 2,9750 | kg |
| *Blanching and Drying* | | | |
| Bulk conveyer | Infrastructure | 12,0000 | kg |
| Blanching tank | Infrastructure | 20,0000 | kg |
| Chilling conveyer | Infrastructure | 20,0000 | kg |
| Drum dryer | Infrastructure | 15,0000 | kg |
| Fan-heater | Infrastructure | 8,0000 | kg |
| Bags | consumables | 2,0000 | kg |
| General consumables | Consumables | 2,0000 | kg |
| Electricity for drying | consumable | 0,1712 | kwh |
| Fuel for blanching | consumable | 29,7500 | kg |
| *Freezing* | | | |
| Plate freezer | Infrastructure | 25,0000 | kg |
| Freezing storage | Infrastructure | 15,0000 | kg |
| Storage boxes | Infrastructure | 4,0500 | kg |
| Electricity for freezing unit | Consumable | 0,4566 | kwh |
| Electricity for storing kelp | Consumable | 0,0274 | kwh |
| *Waste* | | | |
| Solid organic waste | | 50,0000 | kg |

The values were referred to the FU. The primary data were provided by the company and were supplemented with secondary data obtained from literature.

Several assumptions were made when the inventory was drawn up, due to lack of information or for reasons of system modelling.

The sometimes-insufficient specific information, lead to choose the best scenario to attribute to the data. In fact, most seaweed production processes were not already entered in the Ecoinvent database. It was therefore necessary to simplify the inputs of the process by entering the value of the most probable or most characteristic construction material.

The choice of pipe material was part of this case. The pipes, in which the robes with seeds are wrapped, are composed by different types of plastic. Thus, it was assumed that the building material was polyethylene. Similar assumptions was made for working gears and general consumables.

Another type of assumption was made during the input of the tanks for incubation. These are formed from steel, plastic and glass fibers. Since a similar process was not already present in Ecoinvent, it was assumed that most of the tank was made of polyethylene. Similarly, the lighting system was assumed to be made of steel, such as the microscope and the scale.

In addition, the absence of processes in the database prompts to choose the raw material and consider its weight. The chains used in the cultivation were supplied with a length value and, in order to calculate their impact, it was necessary to choose the raw material (stainless steel) and calculate its weight. Similarly, it was done for strings and pipes, for which volume and density were calculated.

This LCA also includes a waste scenario for production scraps and waste, produced during the process. Every year the wastes was (already referred to the FU): 3 kg of packaging waste, 3 kg from general consumables, 5 kg of ropes and finally 50 kg of solid organic material. The latter consists in kelp parts that cannot be used as grasping organ and represents 10% of the total annual production. The end-of-life scenario of waste was modelled assuming a recycling percentage of 27% for polypropylene (PP) (Syversen et al., 2019) and 65% for polyvinylchloride (PVC) (Frane et al., 2019). The non-recycled material was disposed of in incinerators. The organic waste was treated as a terrestrial organic waste (e.g., scraps from agriculture) and disposed of with municipal incinerators. In no case, transport was considered.

Finally, the positive impacts of carbon bioremediation and nutrient uptake were calculated. Carbon absorption by algae was reported as a negative water emission of 39.6 kg of carbon. Similarly, it was done by inserting a negative emission into water for 4.08 kg of nitrogen and 0.4 kg of phosphorus (Thomas et al., 2020).

Again, according to Thomas et al., (2020) the values entered corresponded respectively to the elimination from the sea of 145 kg of $CO_2$ equivalent and the decrease in eutrophication of 2.82 kg of $PO_4$ equivalent.

### 4.4.3 Software, database and methods used

The thesis was developed using the SimaPro Software and Ecoinvent 3.8 database, installed by default. The ReCiPe method and CML-IA baseline method, both updated to 2016, preinstalled in the software, were used

The two calculation methods have been chosen to satisfy the two objectives of the thesis: provide information with potential decision-making value on the improvement of the most critical processes and compare the results with the literature to support the thesis results. To satisfy the intent of the first point, the ReCiPe method was chosen, while for the second point the CML method is more suitable.

Recipe, unlike CML, calculates a larger number of impact categories (18 categories) than CML (11 categories). ReCiPe, compared to CML, considers the impact categories of ionizing radiation, land use and particulate matter formation. For this reason, ReCiPe allows one to have a broader and more specific view of the potential impacts generated by the process. The CML method is used to compare the results of the thesis with other similar studies. According to Thomas et al., (2020) and Koesling et al., (2021) the CML method is the most widely used method in LCA studies, ensuring the comparability of different research. The method guarantees significant impact categories for the purpose of a sustainability analysis, it is a well-documented and a widely established method in research.

Finally, the results are analyzed through the endpoint level of ReCiPe. Using endpoints, the effects of impacts are highlighted, making the understanding of impacts clearer and more immediate.

# 5. Results: impacts assessment

The following section describes the results of the LCA. The environmental impact analysis was performed using the ReCiPe and CML-IA baseline methods.

The CML method calculated the midpoint impacts. With the ReCiPe method the analysis was done at midpoint and endpoint levels.

## 5.1 CML-IA baseline: midpoints

Table 5 shows the characterized values for each impact category, referring to the total quantity seaweed production, without waste and, finally, only for waste. In Appendix B, one can see the percentage of impact by each single input.

*Table 5: Characterized values for each impact categories, with CML-IA baseline*

| Impact category | Unit | Total | 1 tonne of seaweed | Waste |
|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 3,15E-02 | 3,14E-02 | 8,97E-05 |
| Global Warming Potential | kg CO2 eq | 1,70E+03 | 1,52E+03 | 1,74E+02 |
| Ozone layer depletion | kg CF-11 eq | 1,32E-04 | 1,25E-04 | 7,36E-06 |
| Human toxicity | kg 1,4-DB eq | 1,93E+04 | 1,85E+04 | 8,22E+02 |
| Freshwater acquatic toxicity | kg 1,4-DB eq | 4,07E+03 | 3,90E+03 | 1,70E+02 |
| Marine acquatic ecotoxicity | kg 1,4-DB eq | 5,14E+06 | 4,86E+06 | 2,77E+05 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 3,75E+01 | 3,59E+01 | 1,61E+00 |
| Photochemical oxidation | Kg C2H4 eq | 5,63E-01 | 4,27E-01 | 1,36E-01 |
| Acidification | kg SO2 eq | 8,60E+00 | 8,23E+00 | 3,69E-01 |
| Eutrophication | kg PO4-- eq | 2,37E-01 | -3,79E-01 | 6,16E-01 |

Figure 10 shows the impact percentages of each phase, for each impact category. The hatchery has low impact values, about 2-5%, while it has no impact for the category of AD, HT, MET (<1%) and EU (<1%).

Cultivation is the phase with high percentages for most categories; it varies between 30-45% except in GWP100 (6%) and EU (1.5%). The highest values, 49%, are in AD and HT. The collection contributes around 3-15% in all categories, except for HT where there is no impact and in the EU category where it is 1.47%.

The blanching and drying phase is, after the cultivation, the one with the highest percentage of impact (about 25%), while it generates 5% of the impact in the EU category. Values with 10-15% are associated with the freezing phase.

Finally, waste contributes more to the impact in the PO category (24%), while it is absent in the GWP100 and AD. In other categories it fluctuates around 5%.

A note should be made to eutrophication: all the phases of the process generate a total impact of 65% and the capture of phosphorus and nitrogen contribute to reduce the impact on the EU by -12%.

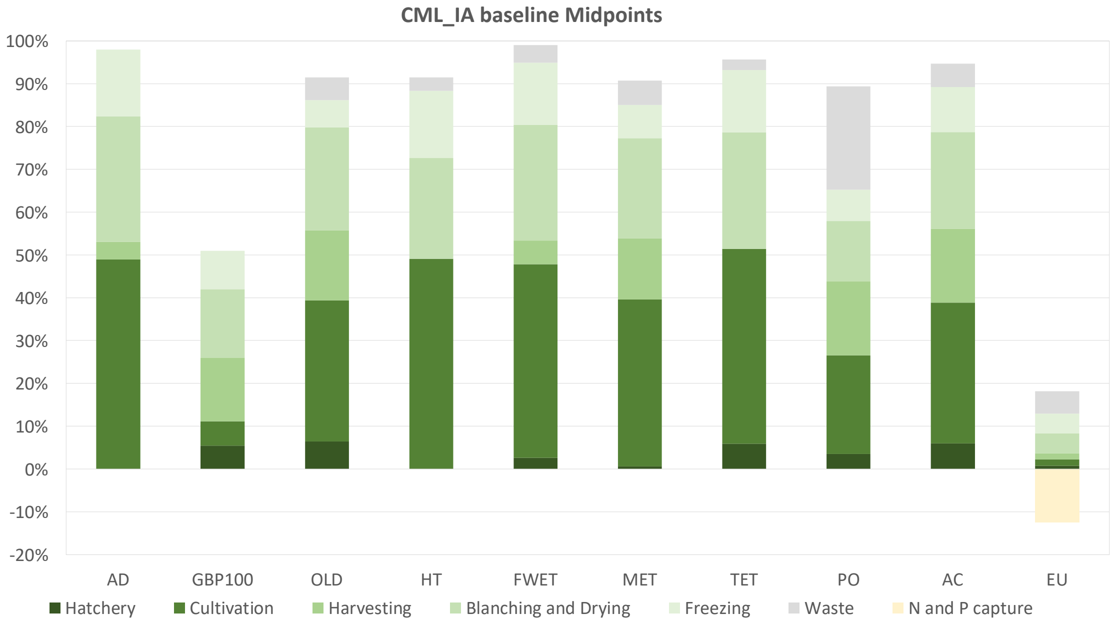

*Figure 10: Impact values percentage for each impact categories at midpoint level, with CML-IA baseline method*

To analyse in more detail the contribution of the processes and change the point of view, an aggregation of the data in three macro-inputs was carried out: structures, energy consumption and machinery. More specifically:

- infrastructures are considered: blanching tank, freezing storage, ropes (8 mm), anchor, chain, and vessel
- among the machinery are considered: machinery on vessel, bulk conveyer, chilling conveyer, drum dryer and plate freezer.
- consumptions include: electricity for water filtration, fuel for cultivation and blanching.

In this analysis the contribution of the impact generated by waste scenarios was excluded, because the aim was to observe only the role of structures and their materials.

Figure 11 shows the percentages of impacts for each impact category for structures, machinery and consumption.

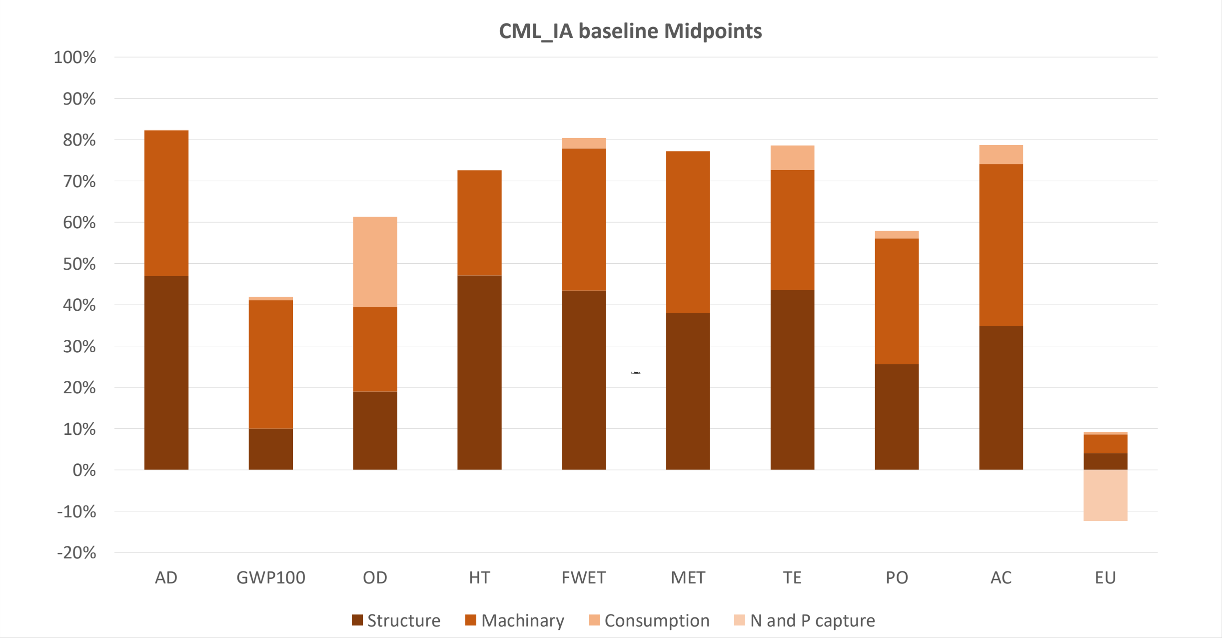

*Figure 11: Impact values percentage for structure, machinery and consumption, for each impact categories, at midpoints level, with CML-IA baseline*

The structures have the highest impact rate (about 40%), however for the GWP100 has 10% impact. In the OD category, it has an impact of 19% (less than the one caused by machinery, 21%), for the PO it has 25% (less than 31% produced by machinery) and for AC it shows 35% (less than 39% caused by machinery). The machinery has percentages around 30-40% and for MET the impact is 39%.

Consumptions have low impact values, about 5% in almost all categories; they have no impact for AD and GWP100.

Finally, nitrogen and phosphorus uptake generate a mitigation of -12% of impacts, while the remaining processes participate in the total 11% of impacts.

## 5.2 ReCiPe: midpoints and endpoints

From the midpoint analysis via ReCiPe, the results are shown in Table 6. The table expresses the values of the characterization, where each category of impact has its own unit and the values are not comparable between the different categories of impact. Due to ReCiPe was chosen for investigating all the possible impacts of production, all categories were considered.

In Appendix B, one can see the percentage of impact by each single input, both for midpoint and endpoint.

*Table 6: Impact values for each impact categories, at midpoints level, with ReCiPe method*

| Impact category | Unit | Total | 1 tonne of seaweed | Waste |
|---|---|---|---|---|
| Global Warming Potential | kg CO2 eq | 1,56E+03 | 1,42E+03 | 1,44E+02 |
| Stratospheric ozone depletion | kg CFC11eq | 3,51E-03 | 1,17E-03 | 2,34E-03 |
| Terrestrial Ecotoxicology | kBqCo-60 eq | 2,44E+02 | 2,38E+02 | 5,67E+00 |
| Ozone formation | kg Nox eq | 4,70E+00 | 4,07E+00 | 6,32E-01 |
| Fina particulate matter formation | kgPM2.5 eq | 6,87E+00 | 4,86E+00 | 2,01E+00 |
| Ozone formation Terrestrial | kgNOx eq | 4,80E+00 | 4,17E+00 | 6,31E-01 |
| Terrestrial acidification | kg SO2 eq | 7,01E+00 | 6,74E+00 | 2,75E-01 |
| Freshwater eutrophication | kg P eq | 6,82E-01 | 5,58E-01 | 1,24E-01 |
| Marine eutrophication | kg N eq | 6,74E-02 | 3,87E-02 | 2,88E-02 |
| Terrestrial ecotoxicity | kg 1,4DCB | 2,71E+04 | 2,55E+04 | 1,64E+03 |
| Freshwater ecotoxicity | kg 1,4DCB | 1,36E+02 | 1,03E+02 | 3,33E+01 |
| Marine ecotoxicity | kg 1,4DCB | 7,33E+05 | 4,83E+05 | 2,50E+05 |
| Human carcinogenic toxicity | kg 1,4DCB | 5,40E+04 | 5,25E+04 | 1,47E+03 |
| Human non-carcinogenic | kg 1,4DCB | 4,86E+05 | 3,38E+05 | 1,48E+05 |
| Land use | m2a crop eq | 4,60E+01 | 4,41E+01 | 1,91E+00 |
| Mineral resource scarcity | kg Cu eq | 1,16E+02 | 1,15E+02 | 4,40E-01 |
| fossil resource scarcity | kg oil eq | 5,09E+02 | 5,36E+02 | -2,65E+01 |
| Water consumption | m3 | 1,04E+02 | 1,06E+02 | -1,50E+00 |

While total impact values are expressed in table 6, Figure 12 shows the contributions of the different process stages to the total impact value. The values are expressed as a percentage.

The hatchery has low impact rates, about 0-10%, for all impact categories, although presents a 85% contribution in water consumption and 27% in terrestrial toxicity.

For all impact categories, except ozone depletion, marine eutrophication and water consumption, the cultivation phase generates impacts between 20-30%; higher values are observed in the category of terrestrial ecotoxicology, human carcinogenic toxicity (47%) and a 50% shortage of mineral resources.

The harvest shows contributions around 10-15% in almost all impact categories, except for ozone depletion and water consumption with a 7%.

The blanching and drying phase is similar and has values around 15%. For this phase, values far from the mean value are observed for the categories of ozone degradation (0%), marine eutrophication (6%), terrestrial ecotoxicity and human carcinogenic toxicity of 28%. The freezing phase has impacts of around 8-10% for each impact category, excluding values of 15% for terrestrial ecotoxicity, human carcinogenic toxicity and mineral resources scarcity.

Finally, the impacts generated by waste scenarios have high values for the categories of ozone depletion (64%) and marine ecotoxicity (34%), while the other categories, they fluctuate between 10-20%. Low impacts of waste scenarios occur for terrestrial ecotoxicology (5%), while negative values for the scarcity of fossil resources (-5%) and the consumption of water (-1.20%).

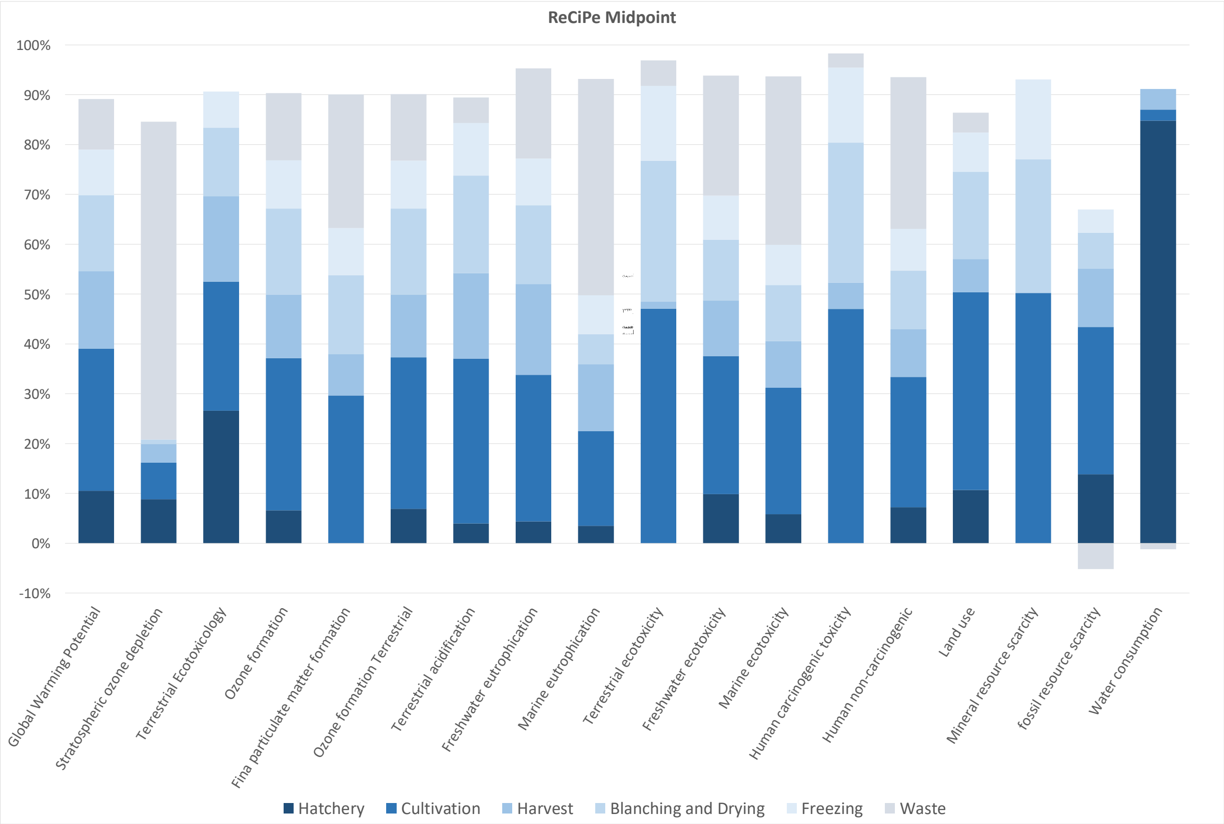

*Figure 12: Impact values percentage at midpoint for each impact categories, with ReCiPe method*

As in the CML method, three groups of macro-inputs are built: structures, machinery and consumption. Moreover, such in CML, the contribution of the impacts generated by waste scenarios was excluded too.

In Figure 13, the percentage values of the different contributions are represented. In the categories of impact terrestrial ecotoxicity, human carcinogenic toxicity and mineral resources scarcity dominate the percentages of structures impact, with a 60% on the total value. The facilities generate an impact of 2% for the water consumption category.

Impacts for ozone depletion, ionizing radiation and water consumption, are characterized by values of consumption respectively of 9%, 34% and 85%; consumption do not produce impact in the creation of fine particulates. Values between 25-35% are the machinery contribution to the impact. These values are high, but lower than those of the structures.

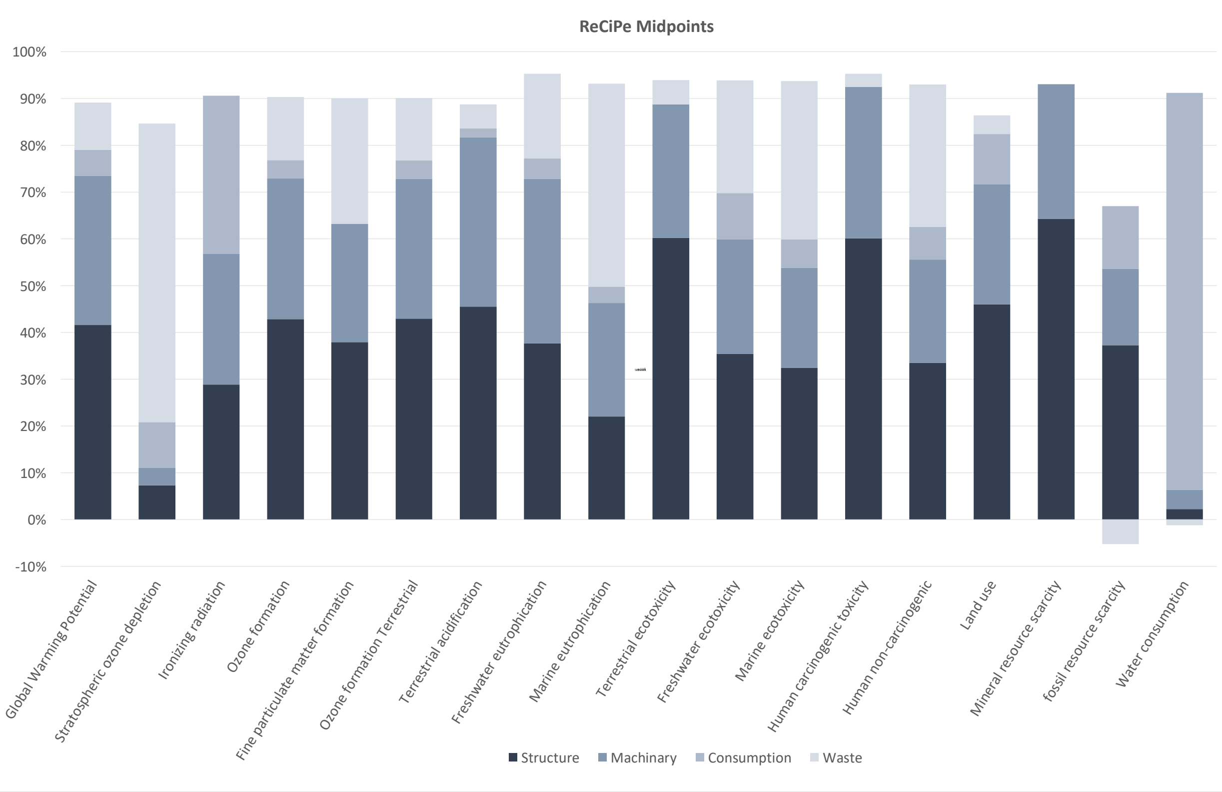

*Figure 13: Impact values percentage for structures, machinery, and consumption, at midpoint for impact categories, with ReCiPe method*

The values calculated at endpoints level are observed in the table 7 which shows represents both the values according to the characterization (total impact in relation to a unit) and the normalized values that are dimensionless and can be compared with each other.

*Table 7: Impact values at endpoint level, with ReCiPe method*

| Damage assessment | | | | |
|---|---|---|---|---|
| Impact category | Unit | Total | 1 tonne of seaweed | Waste |
| damage to human health | DAILY | 1,34E-01 | 2,72E-01 | 4,18E-01 |
| damage to ecosystem quality | species·yr | 1,20E-04 | 8,96E-05 | 3,10E-05 |
| damage to resource availability | dollar | 1,84E+02 | 1,96E+02 | -1,16E+01 |

| Normalization | | | |
|---|---|---|---|
| Impact category | Total | 1 tonne of seaweed | Waste |
| damage to human health | 3,52 | 3,05 | 0,468 |
| damage to ecosystem quality | 0,142 | 0,106 | 0,0357 |
| damage to resource availability | 0,00657 | 0,00698 | -0,000413 |

Figure 14 shows the percentage impact values for each production step. For all three categories, the highest impact (30-38%) is given by cultivation. Harvest phase has a value of 7-10%, while hatchery phase has values of 26% in resources damage category. Blanching and drying contribute on average of 15-23% of impacts, while the freezing phase shows values between 7-12%. Finally, waste contributes to the impact on the ecosystem for 25%, while it presents a negative value (-6%) for the category of damage to resource

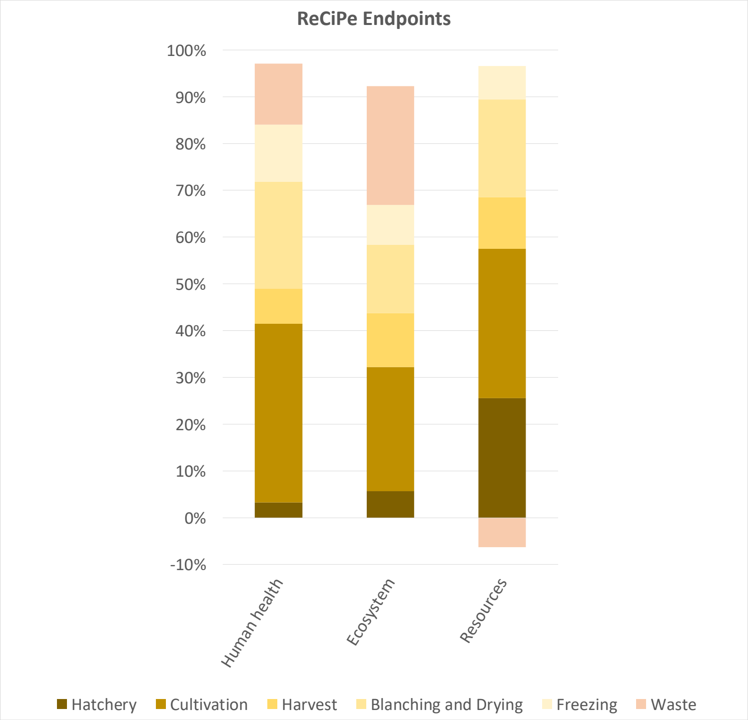

*Figure 14: Impact values at endpoints level, with ReCiPe method*

# 6 Discussion: interpretation

## 6.1 CML and comparison with literature

LCA studies about aquaculture are reported as literature, for a comparison. Literature values are obtained via the CML-IA baseline method, for cradle-to-gate life cycle and for 1 tonne of product (seaweed, fish or shellfish).

Once other papers results were expressed in Table 8, the results of this thesis can be studied in relation to them. Although different aims of other papers, the impact assessment analysis procedures are similar to this study and therefore it is possible to proceed with the comparison. Thomas et al., (2020) and Oirschot et al., (2017) papers allow one to compare similar LCA studies on seaweed farming cultivation. While the papers of Kallitsis et al., (2020) and Aubin et al., (2017) are used to compare the seaweed cultivation sustainability, respectively with fish and shellfish farming sectors.

*Table 8: Results from literature*

| Impact Category | Unit | This Study | Thomas et al., 2020 | Oirschot et al., 2017 | Kallitsis et al., 2020 | Aubin et al., 2017 |
|---|---|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 3,15E-02 | 2,19E+00 | 1,39E+02 | 5,95E-03 | - |
| Global Warming Potential | kg CO2 eq | 1,70E+03 | 5,93E+01 | 2,17E+04 | 1,89E+03 | 9,52E0 ± 15,75 |
| Ozone layer depletion | kg CF-11 eq | 1,32E-04 | 1,49E-04 | 2,50E-03 | 3,56E-04 | - |
| Human toxicity | kg 1,4-DB eq | 1,93E+04 | 1,93E+02 | 2,22E+04 | 2,82E+03 | - |
| Freshwater acquatic toxicity | kg 1,4-DB eq | 4,07E+03 | 1,49E+02 | 5,94E+03 | - | - |
| Marine acquatic ecotoxicity | kg 1,4-DB eq | 5,14E+06 | 1,54E+05 | 7,73E+06 | 6,15E+06 | - |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 3,75E+01 | 2,35E+00 | 8,12E+01 | 1,93E+02 | - |
| Photochemical oxidation | Kg C2H4 eq | 5,63E-01 | 8,97E-02 | 3,82E+00 | 2,83E+00 | - |
| Acidification | kg SO2 eq | 8,60E+00 | 1,26E+00 | 5,39E+01 | 3,03E+01 | 2,04E00 ± 0,61 |
| Eutrophication | kg PO4-- eq | 2,37E-01 | 7,78E+01 | 1,15E+01 | 1,89E+02 | -8,9E-01 ± 0,8 |

In Thomas et al., (2020), the seeding phase is the highest values in marine ecotoxicology category (49 kg 1,4-DB eq) and contributes to 22% of the total impacts for the photochemical oxidation impact category. For other categories, seeding has impact values about 1-3%, except for global warming potential to which contributed by 13%. The drying phase consists of 83% of the total impact of global warming potential, while it contributes 40-50% for the categories of fresh water ecotoxicity, marine ecotoxicity, acidification and eutrophication. Finally, the freezing phase generates a high impact for marine ecotoxicity and contributes 50-70% to the total impact in categories of ozone depletion, human toxicity, fresh water ecotoxicity, terrestrial ecotoxicity and acidification.

In Oirschot et al., (2017), infrastructure has the highest percentage of total impact, for most impact categories. Infrastructure includes steel chain, anchor, ropes, buoys and strip strengtheners. In the impact categories of human toxicity and fresh water ecotoxicity, infrastructure has the 85-86% of impact, while for marine ecotoxicity has the 70%. In addition, infrastructure contributes to 41% of impacts in eutrophication and terrestrial ecotoxicity. Infrastructure participates 25% in the impact of global warming potential and about 5-10% for acidification and ozone layer depletion.

As a justification for some general differences in the results of the three papers about seaweed farming, a first observation about inputs choice in SimaPro should be made. Thomas et al., (2020) and Oirschot et al., (2017) chose processes derived from the Ecoinvent *market*, while processes from *transformation* were chosen in the thesis. Processes belonging to the *market* are recommended when no in-depth process information is provided. With this choice, the analysis is carried out focusing on economic value than on the environmental one. Only products and transport impacts are considered. Therefore, inputs from *market* have less impacts than those of *transformation*. The latter includes the inputs for the realization of the product, the energy used for its realization and finally the waste and emissions generated by its production. The *transformation choice* allows one to have more comprehensive impact data and it is more oriented to environmental aspects (SimaPro.com).

Comparing characterized values of the thesis with those of the literature, it emerged some proximity between the values, but also some discrepancies. Among the three studies the differences for the category of global warming potential are evident. The highest difference is observed between the thesis values (1530 kg $CO_2$ eq) with Oirschot et al., 2017 (21 700 kg $CO_2$

eq), and those of Thomas et al., (2020) (59,1 kg CO2 eq). The GBP100 is most influenced by drying operation in both the following study and Thomas et al., 2020. Then, the drying methods were compared, and it turned out that they are different processes. In Thomas et al., 2020 air cabine is used, in PurSea drum dryers and fan-heaters are used and, at least, in Oirschot et al., a maize drying was considered. In addition, Thomas et al., 2020 considers the MJs of energy consumed by the machine at the stage, while for the thesis and in Orschot et al., (2017) the weight of machinery components was considered. The high impact of drying suggests looking for more environmentally friendly methods at this stage. Drying is a fundamental phase of algae processing and therefore cannot be omitted. However, according to Oirschot et al., 2017 it is possible to think about methods that use solar heat or wind to dry algae, generating lower impacts.

Impact category of human toxicity has different values for each study. The results between the thesis and Thomas et al., 2020 differ the most. In the thesis results, in line with Oirschot et al., (2017), the cultivation phase dominates the impact due to the infrastructure at sea. Conversely, in Thomas et al., 2020 the freezing phase contributed most to human toxicity, considering the energy consumed by the machinery for its operation. Since the toxic elements of the impact category are chromium VI and arsenic emitted from stainless steel production, the impact values for the thesis are higher than those of Thomas et al., 2020.

For impact categories of fresh water ecotoxicity, water ecotoxicity and terrestrial ecotoxicity, the following study and Oirschot et al., 2017 present similar values, but higher than those of Thomas et al., 2020. The reasoning previously made for human toxicity is valid even now. Indeed, for Thomas et al., (2020) the greatest impact is attributed to the freezing phase, while in the thesis the impact is due to the infrastructure necessary for the cultivation at sea.
Due to the impact of acidification, the results of the thesis do not differ greatly from those of Thomas et al., 2020. In both studies, hatchery and cultivation, which have similar procedures, dominates the impacts.

The three studies present different values for the depletion ozone category. For the construction of metal machinery, which are the major constituents of the impact category, NOx is produced during welding. In the thesis, in which the machinery has the greater impact than the other two articles, the three largest contributors to emissions are made of steel (anchors, machinery, chains).

Finally, differing values are also observed in the category of impact of eutrophication. Both in Thomas et al., (2020) and in the thesis, negative values are observed, respectively -5,48 kg $PO_4^{--}$ equivalent and - 0,379 kg $PO_4^{--}$ equivalent. Thomas et al., (2020) states that every tonne of algae absorbs nitrogen and phosphorus corresponding to 2.82 kg $PO_4^{--}$ equivalent.

To conclude, after the comparison, machinery and infrastructures are the greater contributors to the impact categories; moreover, various methods of production can generate different impacts.

At this point, it is interesting to make a comparison between impacts generated by seaweed production chain and that of other aquaculture sectors.

Kallitsis et al., (2020), investigates the sustainability of the production chain of a breeding of sea bream, through an LCA study. The high electricity consumption by fish rearing generates 49% of the GWP. While feed fish production generates the highest percentage of impact in the impact categories of AD, OD and PO.

The comparison with this study, showed that environmental footprint of CO2 equivalent is similar to the seaweed one, as one can see in Table 8. Instead, it is noted that seaweed production presences minor impacts in eutrophication category, due to the uptake capacity of nitrogen and phosphorus of plants.

Finally, thanks to the Aubin et al., (2017) paper, the values of shellfish production are compared. The fuel used in the different stages of farming contributed by 85% of the GWP, while the infrastructure produced 15% of the impact and the bouchots the 16%. The on-farm growing phase contributed to 85% of the eutrophication category. However, the impacts are mitigated by high carbon removals mainly due to shellfish growth.

The comparison with shellfish production (Aubin et al., 2017) showed that for the categories of climate change, acidification, and eutrophication the values presented by shellfish are significantly lower than those of algae production. There are two reasons for this difference in values: the rate of carbon sequestration by shellfish and the greater knowledge of the production processes of shellfish culture.

According to Aubin et al., (2017) the seized carbon thanks to shellfish production is due both to the materials used (wooden stakes) and to the growth of animals that incorporate carbon into their shells. The total value of carbon sequestration is 216 kg $CO_2$ equivalent, which is significantly higher than that calculated by Thomas et al., of 145 kg $CO_2$ equivalent. The same applies to nitrogen and phosphorus values seized during shellfish growth (4,55 kg $PO_4^{--}$ equivalent), which is higher than algae (2,82 kg $PO_4^{--}$equivalent).

Finally, shellfish farming in Europe has been extensively studied since the early 2000s (Ziegler et al. 2003) and presents an extensive literature of studies on its sustainability. This has contributed to the development of the production system, making it more environmentally efficient. Conversely, seaweed cultivation industry is still an emerging sector in Europe and also literature on its sustainability analysis, justifying a lower efficiency.

## 6.2 ReCiPe and the hotspots

The midpoint results calculated with ReCiPe allow one to highlight some hotspots of the different production steps. The results showed high impact rates for most impact categories, for processing (blanching, drying and freezing) due to the presence of machinery. Machinery was included in the inventory approximating their structure to the material that most constitutes them. It would be interesting and closer to the reality of the impacts, to carry out an analysis in which instead of the mass of the machinery, the energy consumed for operation is used. The information that could be obtained might be more usable by the company within a decision-making process. In addition, it may be less impactful as Norway energy mix consists of around 91% renewable resources.

In this respect, interesting results were observed for energy inputs. Along the production chain, electricity is used in several stages (electricity for filtration, collection, blanching, drying and freezing), but only electricity for filtration had an impact. This is probably due to initial input in the inventory that was 100 times larger than the other inputs.

Instead, with same quantity inserted in the inventory, the fuel has participated to the formation of impacts although in percentages under the 4%. This shows that the energy impacts from electricity are very low due to the characteristics of the mix.

The results also highlighted how machinery and infrastructure, especially steel chains and anchors, contribute strongly to the impact categories. Impacts from machinery and infrastructure are due to compounds such as carbon dioxide, carbon monoxide, methane, chlorofluorocarbons, nickel, dichlorobenzene etc. These compounds are produced from processing of plastic and steel (made of chromium alloy) material, of which machinery and infrastructure are made.

Stainless steel used for equipment such as anchors and chains, is certainly essential in aquaculture sector, but clearly is not an environmentally sustainable choice. According to Oirschot et al., (2017) alternatives to stainless steel should be found to reduce impacts, or at least their use should be minimized. So as a hint, concrete anchors should be used instead of steel.

A discussion on the waste treatment scenario is also important. In most LCA analyses, waste treatment is not considered because it often depends on other external companies. However, the data for the thesis also presented information on waste. The results showed some hotspots about waste, but it should be said that this could be an overestimation or underestimation of the impact. In fact, most of the contributions to the impacts of waste are made by organic solid material. The end of life of this waste is not necessarily incineration, as was assumed, instead, for this study. This explains the rejection representing a hotspot for the category of impact of eutrophication and depletion ozone layer. The incineration of organic material produces sulphur and nitrogen compounds, carbon dioxide or carbon monoxide, which are the impacting elements for those impact categories.

In the category of fossil resource scarcity impact, a negative impact value is found. Indeed, the fact that 65% of PVC has been recycled has contributed to a positive impact on the environmental system.

Therefore, careful waste management and a high recycling rate could greatly affect the environmental sustainability of the company.

Finally, ReCiPe, unlike CML-IA, distinguishes the contribution of nitrogen or phosphorus in increasing eutrophication. Eutrophication is produced more by the phosphorus as indicated in freshwater eutrophication (0,682 kg P equivalent), while nitrogen contributes less, as evidenced by the marine eutrophication. Being able to distinguish the contributions of N and P is essential to understand the impact scenario. In fact, eutrophication leads to the aquatic biodiversity alteration (Huijbregts et al., 2016), but through different paths: phosphorus contributes to increase of etheretrophous species, algae and cyanobacteria, while nitrogen generates plankton biomass proliferation leading to anoxia conditions in aquatic environment. However, these values do not allow tangible information about the effects on biodiversity due to algae cultivation, representing a limit of LCA (Thomas et al., 2020). In order to safeguard the possible loss of biodiversity, various proposals for infrastructure are developed, for example: using hallow anchors for shelter and life from animals or using other anchorage structures that act as substrate for the coral reefs growth (Hardison, 2014).

# 7. Conclusions

The thesis investigated the environmental sustainability of seaweed production of the Norwegian company PurSea, through an exploratory life cycle analysis for 1 tonne of seaweed in fresh weight.

Following an introduction on seaweed characteristics and their role in the global and European socio-economic context, research was carried out on existing literature about the sustainability assessment of macroalgae sector, through LCA studies. Subsequently, knowledge about LCA methodology was deepened and the case study analysis was established. The SimaPro software calculated impacts of all the impact categories for ReCiPe and CML-IA baseline methods, in order to meet both objectives of the thesis: assess the presence of critical environmental impact situations, to improve the environmental performance of the supply chain, and compare the sustainability of seaweed production with the values of fish and shellfish farming.

Once impacts were calculated, the results showed two main impacts sources. The first came from cultivation at sea, caused mainly by the following infrastructures used: stainless steel anchors and chains. The second environmental impact source was generated by the processing phase of fresh algae, due to the machinery used for blanching, drying and freezing. In fact, for calculating the impact, the machinery was defined according to the main material used, which is stainless steel. During the discussion of the results, some suggestions were provided to try to minimize the impacts of these phases.

The waste treatment analysis showed that the impacts are low, excluding some impact categories, and it was argued that a high recycling rate can help further decrease impacts. Finally, the lower impact value is the hatchery, whose impact is caused only by the high electricity used for filtration.

During the results discussion, possible or already used alternatives in the aquaculture sector were proposed to try to reduce the environmental impacts highlighted in the analysis. Alternatives, include using more environmentally friendly materials or designing lower impact alternative processing systems.

However, there are other environmental impacts that LCA is unable to detect and calculate, such as the microplastics introduction in aquatic environment, produced by the degradation of polypropylene and polyvinylchloride ropes and buoys (Oirschot et al., 2017 and Thomas et al., 2020).

Comparison with the literature, revealed some discrepancies between the results of the different studies on algal culture. The comparison evidenced that the differences were caused by the choice of different inputs in the inventory phase, and from the diversity of some processing phases for seaweed exiled.

Finally, the comparison with other aquaculture sectors, for only some categories of impact, showed that impacts calculated in the thesis were comparable with those generated by the breeding of sea bass and sea bream. Conversely, the results of the thesis were very far from the values of shellfish farming, because shellfish seize a greater carbon amount than algae, and also the shellfish industry is more studied than the emerging algae under the point of view of environmental efficiency.

The analysis revealed some critical issues that allowed one to indicate some suggestions for the supply chain efficiency. However, the changes that should be made to mitigate impacts would require significant economic investment.

However, exploratory studies, such as this thesis, can contribute to increase information for a future development of seaweed farming sector (Seghetta et al., 2017). As the cultivation of seaweed in Europe continues to increase, research for more efficient infrastructure and machinery should be encouraged (Oirschot et al., 2017). In addition, the quality of the analyses and the life cycle assessment capabilities should be increased, in order to assess emerging environmental impacts on marine environments, such as the production of microplastics at sea (Thomas et al., 2020).

# Acknowledgments

I would like to dedicate this last page of my thesis for some acknowledges. First of all, my gratitude to Professor Pastres for having accompanied me in the field of environmental sustainability through the life cycle assessment and allowed me to satisfy my curiosity. I gratefully acknowledge avaibility and kindness of Carl and Christian who provided the data for this thesis.

My thanks to those I dear to me, who love me for the “crooked vine” I am, to quote Massimo Recalcati. Crooked vines represent each of us, with our imperfections, our attitudes, our needs and our oddities. So, if I am writing these thanks, is because the people closed to me trusted in me, despite everything.

Thank you so much to my mother, who defended me with stubborn tenacity from the bad weather of life and spurred me to become the woman I am becoming. Thanks mom who is my greatest reference. Thanks to my father, who always guaranteed me the best life I could have, always allowing me the luxury of choice. And to my brother, thank you for being my first confrontation with the world, the crooked screw next to me that twisted its branches with mine, strengthening my structure.

From my heart, a big thank to Agnese, who is not only a university colleague or my best friend, but she is a true life companion for me. In my last five years, there hasn’t been an experience, a milestone, or an emotion that I haven’t shared with her and for that I am immensely grateful to the destiny that brought us together (by mistake, in that lab). I am happy and proud to wear the laurel wreath with her and think, once again, that "we" together concluded this magnificent experience.

I would also like to thank my closest friends who have contributed, each in their own way, to getting me here. I feel like a collection of the best parts of you and that is why I want to thank Filippo and Margherita, with affection.

Last but not least, a huge thank you to Matteo. I have never known a man so caring and protective as you, who loved me even in my less serene moments. Thank you for your love.

With these last lines, a chapter of my life is ending, which enriched me with love, joy, friendships, knowledge and awareness of myself.

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# Appendix A

| Item | Typology | Ammount | Life Time | Value to FU | Unit | Process in Ecoinvet |
|---|---|---|---|---|---|---|
| ***Hatchery*** | | | | | | |
| Tanks | Infrastructure | 1000 | 30 | 3,3333 | kg | Polyethylene, high density, granulate {RER}\|production\|Cut-off, U |
| Pumps | Infrastructure | 45 | 30 | 0,1500 | kg | Steel, chromium steel 18/18 {RoR}\|Steel production, converter\|Cut-off, U |
| Pumping station | Infrastructure | 40 | 30 | 0,1333 | m3 | Concrete, normal {RoR}\| unreinforced concrete, producion with cement CEM II/B \|Cuf-off, U |
| Pipes | Infrastructure | 1081 | 10 | 10,8100 | kg | Polyvinylchloride, suspension polymerised {RER}\| |
| Lighting system | Infrastructure | 20 | 30 | 0,0667 | kg | Steel, chromium steel 18/18 {RoR}\|Steel production, converter\|Cut-off, U |
| Seawater filters | Infrastructure | 3 | 5 | 0,0600 | kg | Steel, chromium steel 18/18 {RoR}\|Steel production, converter\|Cut-off, U |
| Microscope | Infrastructure | 10 | 50 | 0,0200 | kg | Steel, chromium steel 18/18 {RoR}\|Steel production, converter\|Cut-off, U |
| Scale | Infrastructure | 1 | 10 | 0,0100 | kg | Steel, chromium steel 18/18 {RoR}\|Steel production, converter\|Cut-off, U |
| Working gears | Infrastructure | 10 | 1 | 1,0000 | kg | Polyvinylchloride, emulsion polymerised {RER}\| |
| Ropes 2mm | Consumable | 100 | 0,1 | 11,3726 | kg | Polypropylene, granulate {RER}\|production\|Cut-uff, U |
| Ropes 8mm | Consumable | 0,1 | 0,01 | 45,4903 | kg | Polypropylene, granulate {RER}\|production\|Cut-uff, U |
| Seawater | Consumable | 113,72 | 1 | 100,0000 | m3 | Water, salt, ocean |
| Freshwater | Consumable | 545,9 | 1 | 1,0000 | m3 | Water, fresh |
| Electricity for filtration | Consumable | 30000 | 1 | 3000,000 | kWh | Electricity, low voltage {NO}\| electricity voltage transformation from medium to low voltage |
| ***Cultivation*** | | | | | | |
| Anchor | Infrastructure | 30000 | 30 | 100,0000 | kg | Steel, chromium steel 18/18 {RoR}\|Steel production, converter\|Cut-off, U |
| Anchoring buoy | Infrastructure | 1606 | 30 | 5,3533 | kg | Polyethylene, high density, granulate {RER}\|production\|Cut-off, U |
| Buoy | Infrastructure | 900 | 30 | 3,0000 | kg | Polystirene expandable {RER}, production |
| Chain | Infrastructure | 7560 | 30 | 25,2000 | kg | Steel, chromium steel 18/18 {RoR}\|Steel production, converter\|Cut-off, U |
| Anchoring rope | Infrastructure | 1250 | 30 | 0,1066 | kg | Polypropylene, granulate {RER}\|production\|Cut-uff, U |
| Longline | Consumables | 1000 | 30 | 1,3042 | kg | polyethylene terephthalate, granulate, amorphous {Eu without Swizzerland} |
| Shakcles | Infrastructure | 50 | 20 | 0,2500 | kg | Iron pellet {RoR}, production |
| Vessel | Infrastructure | 500 | 30 | 1,6667 | kg | Glass fibre reinforced plastic, polyester resinm had-lay up {RER} production |
| General consumables | Consumables | 50 | 5 | 1,0000 | kg | Polyvinylchloride, suspension polymerised {RER}\| |
| Fuel for cultivation | Consumable | 300 | 1 | 25,5000 | kg | Diesel, low-sulfur {Europe without Svizzerland} |
| ***Harvest*** | | | | | | |
| Vessel | Infrastructure | 500 | 30 | 1,6667 | kg | Glass fibre reinforced plastic, polyester resinm had-lay up {RER} production |
| Machinery on vessel | Infrastructure | 3000 | 15 | 20,0000 | kg | Alluminium alloy, metal matrix composite {RoR} |
| Harvest bags | consumables | 20 | 1 | 2,0000 | kg | Polyvinylchloride, emulsion polymerised {RER}\| |
| Fuel for harvesting | consumable | 1200 | 1 | 10,2000 | kg | Diesel, low-sulfur {Europe without Svizzerland} |
| Fuel for preprosessing | Consumable | 297,5 | 1 | 2,9750 | kg | Diesel, low-sulfur {Europe without Svizzerland} |
| Fuel for transporting | Consumable | 297,5 | 1 | 2,9750 | kg | Diesel, low-sulfur {Europe without Svizzerland} |

| | | | | | | |
|---|---|---|---|---|---|---|
| ***Blanching and Drying*** | | | | | | |
| Bulk conveyer | Infrastructure | 1200 | 10 | 12,0000 | kg | Steel, chromium steel 18/18 {RoR}\|Steel production, converter\|Cut-off, U |
| Blanching tank | Infrastructure | 2000 | 10 | 20,0000 | kg | Steel, chromium steel 18/18 {RoR}\|Steel production, converter\|Cut-off, U |
| Chilling conveyer | Infrastructure | 2000 | 10 | 20,0000 | kg | Steel, chromium steel 18/18 {RoR}\|Steel production, converter\|Cut-off, U |
| Drum dryer | Infrastructure | 1500 | 10 | 15,0000 | kg | Steel, chromium steel 18/18 {RoR}\|Steel production, converter\|Cut-off, U |
| Fan-heater | Infrastructure | 800 | 10 | 8,0000 | kg | Steel, chromium steel 18/18 {RoR}\|Steel production, converter\|Cut-off, U |
| Bags | consumables | 20 | 1 | 2,0000 | kg | Polyvinylchloride, suspension polymerised {RER}\| |
| General consumables | Consumables | 100 | 5 | 2,0000 | kg | Polyvinylchloride, suspension polymerised {RER}\| |
| Electricity for drying | consumable | 1500 | 1 | 0,1712 | kwh | Electricity, low voltage {NO}\| electricity voltage transformation from medium to low voltage |
| Fuel for blanching | consumable | 350 | 1 | 29,7500 | kg | Diesel, low-sulfur {Europe without Svizzerland} |
| ***Freezing*** | | | | | | |
| Plate freezer | Infrastructure | 5000 | 20 | 25,0000 | kg | Steel, chromium steel 18/18 {RoR}\|Steel production, converter\|Cut-off, U |
| Freezing storage | Infrastructure | 3000 | 20 | 15,0000 | kg | Steel, chromium steel 18/18 {RoR}\|Steel production, converter\|Cut-off, U |
| Storage boxes | Infrastructure | 810 | 20 | 4,0500 | kg | Polyvinylchloride, suspension polymerised {RER}\| |
| Electricity for freezing uni | Consumable | 4000 | 1 | 0,4566 | kwh | Electricity, low voltage {NO}\| electricity voltage transformation from medium to low voltage |
| Electricity for storing kelp | Consumable | 240 | 1 | 0,0274 | kwh | Electricity, low voltage {NO}\| electricity voltage transformation from medium to low voltage |
| ***Waste*** | | | | | | |
| Solid organic waste | | 500 | 1 | 50,0000 | kg | |

# Appendix B

| | | CML-IA baseline | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Input | Abiotic depletetion | Global Warming Potential | Ozone layer depletion | Human toxicity | Freshwater acquatic toxicity | Marine acquatic ecotoxicity | Terrestrial ecotoxicity | Photochemical oxidation | Acidification | Eutrophication |
| Hatchery | Ropes 8mm | | 5,44% | | | 0,10% | 0,43% | | 3,44% | 3,29% | 0,13% |
| | Pumping station | | | | | | 0,18% | | | | 0,08% |
| | Electricity for filtration | | | 6,37% | | 2,51% | | 5,92% | | 2,67% | 0,53% |
| | Total | | 5,44% | 6,37% | | 2,61% | 0,61% | 5,92% | 3,44% | 5,96% | 0,74% |
| Cultivation | Anchor | 39,10% | | 15,80% | 39,20% | 36,10% | 31,10% | 36,30% | 18,40% | 26,30% | 3,13% |
| | Anchor buoy | | | | | | | | | | |
| | Chain | 9,85% | 5,67% | 3,97% | 9,89% | 9,10% | 7,86% | 9,16% | 4,63% | 6,62% | 0,79% |
| | Vessel for cultivation | | | | | | | | | | 0,05% |
| | Fuel for cultivation | | | 13,20% | | | | | | | |
| | Total | 48,95% | 5,67% | 32,97% | 49,09% | 45,20% | 38,96% | 45,46% | 23,03% | 32,92% | 3,96% |
| Harvesting | Machinary on vessel | 4,07% | 14,90% | 11,10% | | 5,55% | 14,30% | | 17,30% | 17,20% | 2,07% |
| | Total | 4,07% | 14,90% | 11,10% | 0,00% | 5,55% | 14,30% | 0,00% | 17,30% | 17,20% | 2,07% |
| Blanching | Bulk conveyer | 4,69% | 2,70% | | 4,71% | 4,33% | 3,74% | 4,36% | 2,21% | 3,15% | 0,38% |
| | Blanching tank | 7,81% | 4,50% | 3,15% | 7,85% | 7,22% | 6,24% | 7,27% | 3,68% | 5,26% | 0,63% |
| | Chilling conveyer | 7,81% | 4,50% | 3,15% | 7,85% | 7,22% | 6,24% | 7,27% | 3,68% | 6,26% | 0,63% |
| | Drum dryer | 5,86% | 3,38% | 2,37% | | 5,41% | 4,68% | 5,45% | 2,76% | 3,94% | 0,47% |
| | Fan-heater | 3,13% | | | 3,14% | 2,89% | 2,49% | 2,91% | | 2,10% | 0,25% |
| | Fuel for blanching | 0,02% | 0,89% | 15,40% | | | | | 1,75% | 1,90% | 0,08% |
| | Total | 29,32% | 15,97% | 24,07% | 23,55% | 27,07% | 23,39% | 27,26% | 14,08% | 22,61% | 2,43% |
| Freezing | Plate freezer | 9,77% | 5,63% | 3,94% | 9,81% | 9,02% | 7,80% | 9,09% | 4,59% | 6,57% | 0,78% |
| | Freezing storage | 5,86% | 3,38% | 2,37% | 5,88% | 5,41% | | 5,45% | 2,76% | 3,94% | 0,47% |
| | Total | 15,63% | 9,01% | 6,31% | 15,69% | 14,43% | 7,80% | 14,54% | 7,35% | 10,51% | 1,25% |
| Disposal | Ropes waste | | | | | | | 2,48% | 18,50% | | |
| | Solid organic waste | | | 5,37% | | 4,11% | 5,64% | | 3,17% | 5,44% | 2,59% |
| | Packaging waste | | | | 3,11% | | | | 2,45% | | |
| | Total | 0,00% | 0,00% | 5,37% | 3,11% | 4,11% | 5,64% | 2,48% | 24,12% | 5,44% | 2,59% |
| | Phosphorus captur | | | | | | | | | | -5,16% |
| | Nitrogen capture | | | | | | | | | | -7,22% |

**ReCiPe midpoint**

| | Inputs | Global Warming Potential | Stratospheric ozone depletion | Ironizing radiation | Ozone formation | Fine particulate matter formation | Ozone formation Terrestrial | Terrestrial acidification | Freshwater eutrophication | Marine eutrophication | Terrestrial ecotoxicity | Freshwater ecotoxicity | Marine ecotoxicity | Human carcinogenic toxicity | Human non-carcinogenic | Land use | Mineral resource scarcity | Fossil resource scarcity | Water consumption |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hatchery | Ropes 8mm | 5,05% | | | 3,83% | | 4,13% | 3,24% | | | | | | | | | | 13,80% | |
| | Electricity for filtration | 5,47% | 8,84% | 26,60% | 2,76% | | 2,75% | | 4,37% | 3,49% | | 9,85% | 5,82% | | 6,67% | 10,70% | | | 84,80% |
| | Total | 10,52% | 8,84% | 26,60% | 6,59% | | 6,88% | 3,24% | 4,37% | 3,49% | 0,00% | 9,85% | 5,82% | 0,00% | 6,67% | 10,70% | 0,00% | 13,80% | 84,80% |
| Cultivation | Anchor | 22,80% | 5,47% | 18,00% | 24,10% | 23,70% | 24,00% | 26,40% | 23,50% | 15,20% | 37,60% | 22,10% | 20,10% | 37,50% | 20,90% | 31,70% | 40,10% | 18,70% | 2,23% |
| | Chain | 5,75% | | 4,55% | 6,08% | 5,96% | 6,05% | 6,65% | 5,93% | 3,82% | 9,48% | 5,58% | 5,07% | 9,46% | 5,27% | 7,98% | 10,10% | 4,71% | |
| | Vessel for cultivation | | 1,84% | | 0,38% | | 0,38% | | | | | | 0,20% | 0,03% | | | | | |
| | Fuel for cultivation | | | 3,33% | | | | | | | | | | | | | | 6,16% | |
| | Total | 28,55% | 7,31% | 25,88% | 30,56% | 29,66% | 30,43% | 33,05% | 29,43% | 19,02% | 47,08% | 27,68% | 25,37% | 46,99% | 26,17% | 39,68% | 50,20% | 29,57% | 2,23% |
| Harvesting | Machinary on vessel | 15,50% | 3,78% | 17,10% | 12,70% | 8,26% | 12,60% | 17,20% | 18,20% | 13,40% | 1,43% | 11,20% | 9,34% | 5,28% | 9,53% | 6,68% | | 11,70% | 4,14% |
| | Total | 15,50% | 3,78% | 17,10% | 12,70% | 8,26% | 12,60% | 17,20% | 18,20% | 13,40% | 1,43% | 11,20% | 9,34% | 5,28% | 9,53% | 6,68% | 0,00% | 11,70% | 4,14% |
| Blanching | Bulk conveyer | 2,74% | | | 2,90% | 2,84% | 2,88% | 3,16% | 2,82% | | 4,51% | | | 4,50% | | | 4,81% | | |
| | Blanching tank | 4,56% | | 3,61% | 4,83% | 4,73% | 4,80% | 5,27% | 4,71% | 3,03% | 7,52% | 4,43% | 4,02% | 7,51% | 4,18% | 6,34% | 8,02% | | |
| | Chilling conveyer | 4,56% | | 3,61% | 4,83% | 4,73% | 4,80% | 5,27% | 4,71% | 3,03% | 7,52% | 4,43% | 4,02% | 7,51% | 4,18% | 6,34% | 8,02% | | |
| | Drum dryer | 3,43% | | 2,71% | 3,62% | 3,55% | 3,60% | 3,96% | 3,53% | | 5,64% | 3,32% | 3,02% | 5,63% | 3,14% | 4,75% | 6,01% | | |
| | Fuel for blanching | | 0,88% | 3,88% | 1,15% | | 1,20% | 1,91% | | | | | 0,25% | | 0,31% | | | 7,19% | |
| | Total | 15,29% | 0,88% | 13,81% | 17,33% | 15,85% | 17,28% | 19,57% | 15,77% | 6,06% | 25,19% | 12,18% | 11,31% | 25,15% | 11,81% | 17,43% | 26,86% | 7,19% | 0,00% |
| Freezing | Plate freezer | 5,70% | | 4,51% | 6,04% | 5,92% | 6,00% | 6,59% | 5,88% | 7,79% | 9,40% | 5,53% | 5,03% | 9,38% | 5,23% | 7,92% | 10,00% | 4,68% | |
| | Freezing storage | 3,42% | | 2,71% | 3,62% | 3,55% | 3,60% | 3,96% | 3,53% | | 5,64% | 3,32% | 3,02% | 5,63% | 3,14% | | 6,01% | | |
| | Total | 9,12% | 0,00% | 7,22% | 9,66% | 9,47% | 9,60% | 10,55% | 9,41% | 7,79% | 15,04% | 8,85% | 8,05% | 15,01% | 8,37% | 7,92% | 16,01% | 4,68% | 0,00% |
| Waste | Solid organic waste | 4,45% | 63,80% | | 13,50% | | 13,30% | 5,11% | 18,10% | 43,40% | | 12,00% | 18,60% | 2,88% | 22,60% | 3,99% | | | 1,37% |
| | Packagin waste | | | | | 26,80% | | | | | | | | | | | | -5,21% | -2,57% |
| | Ropes waste | 5,70% | | | | | | | | | 5,16% | 12,10% | 15,20% | | 7,86% | | | | |
| | Total | 10,15% | 0,00% | 0,00% | 13,50% | 26,80% | 13,30% | 5,11% | 18,10% | 43,40% | 5,16% | 24,10% | 33,80% | 2,88% | 30,46% | 3,99% | 0,00% | -5,21% | -1,20% |

**ReCiPe endpoint**

| | Input | Human healt | Ecosystem | Resource |
|---|---|---|---|---|
| Hatchery | Pumps | | | 0,03% |
| | Pipes | | | 2,29% |
| | Ropes 2mm | | | 3,97% |
| | Ropes 8mm | | | 15,90% |
| | Electricity for filtration | 3,25% | 5,70% | 3,40% |
| | Total | 3,25% | 5,70% | 25,59% |
| Cultivation | Anchor | 30,50% | 21,20% | 17,90% |
| | Anchor buoy | | | 1,86% |
| | chain | 7,70% | 5,33% | 4,50% |
| | Fuel for cultivation | | | 7,66% |
| | Total | 38% | 27% | 32% |
| Harvest | Machinary on vessel | 7,46% | 11,50% | 7,94% |
| | Fuel for harvesting | | | 3,06% |
| | Fuel preprocessing | | | |
| | Total | 7,46% | 11,50% | 11,00% |
| Blanching | Bulk conveyer | 3,67% | 2,54% | 2,14% |
| | Blanching tank | 6,11% | 4,23% | 3,57% |
| | Chilling conveyer | 6,11% | 4,23% | 3,57% |
| | Drum dryer | 4,58% | 3,17% | 2,68% |
| | Fan-heater | 2,44% | | |
| | Fuel for blanching | | 0,48% | 8,93% |
| | Total | 22,91% | 14,65% | 20,89% |
| Freezing | Plate freezer | 7,64% | 5,29% | 4,47% |
| | Freezing storage | 4,58% | 3,17% | 2,68% |
| | Total | 12,22% | 8,46% | 7,15% |
| Waste | Packaging waste | | | -3,18% |
| | Solid organic waste | 9,93% | 13,70% | 2,94% |
| | General consumable waste | | 11,70% | |
| | Ropes waste | 3,09% | | -6,06% |
| | Total | 13,02% | 25,40% | -6,30% |