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Life Cycle Assessment of Mussel farming in Chioggia, Venice

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Abstract

Due to the increasing challenges in the fight against climate change, the search for new solutions and the development of more sustainable alternatives to traditional businesses plays an essential role. With the food industry among the leading in greenhouse gas (GHG) emissions, researchers are looking for alternative sources of protein with a lower environmental impact. As such, mussels are being considered due to their production's low emissions and reputation as a "green" protein source. Worldwide production is continually increasing by the year to satisfy global demands; thus, it is essential to assess the shellfish production to foster increased sustainability. In this thesis, the environmental footprint of a mussel farming company, located in Chioggia (IT) is assessed using a cradle-to-gate Life Cycle Analysis. The aim of the study is to compare the environmental footprint of fixed pole mussel farm, which requires a depuration process, with an offshore longline mussel farm. The study focuses on three stages of production: mussels grow out, depuration implant, and packaging procedures. Calculations were carried out using the software SimaPro and Ecoinvent as the main database. Both ReCiPe and CML IA baseline were used for estimating four impact categories: global warming (GWP), marine and freshwater eutrophication (EP), terrestrial acidification (AP) and marine ecotoxicity (MAETP). Overall, the environmental footprint of the system is 0.41 kg of CO2 eq, which compared to other aquaculture studies has been proven to be a relatively low value. This means the mussel farming sector can be considered a sustainable production. For all investigated indicators, the main contributions are packaging materials, the electricity consumed by machineries and the boats, while in general the infrastructure and wastes have little relevance. The comparison with offshore longlines mussel farms led to define a similar overall potential impacts, while single contributions vary significantly. Boats have the greatest contribution for offshore systems, while the thesis results show only 1/3 of the overall impact is due to boats and a relevant percentage of the impact due to electricity for machineries. This is probably due the use of bigger boats with packaging equipment for offshore farms, whereas the analysed facility uses smaller boats and travels shorter distances. Farm infrastructures in both farming methods are not very relevant.

Thesis structure

This thesis consists of seven chapters. In the introductory chapter, statistics on worldwide and local mussel farming sector have been analysed, as well as the environmental importance of mussel production. In general mussels provide different environmental services; moreover, their production represents a sustainable business that could help in fighting climate change.

The second chapter describes the aim of the study, while the third chapter introduces the mussel supply chain of the company analysed.

The fourth chapter presents the methodologies applied. In the first part the literature was reviewed in order to help the comparison of the thesis results with other LCA studies on the same aquacultural field. Afterwards the methods applied to the analysis were investigated: from a description of a general LCA procedure, software and the database used to a detailed illustration of the LCA phases applied in the case study. This part comprehends the data and assumption needed to assess the sustainability of the company.

Results of both CML IA baseline and ReCiPe methods are presented in the fifth chapter, while their discussion and interpretation have been carried out in chapter six. Conclusions were drawn in the seventh and last chapter.

List of acronyms

FAO	Food and Agriculture Organization
LCA	Life Cycle Assessment
GHGs	Greenhouse Gasses
EAA	Essential Amino Acids
ISO	International Standard Organization
FU	Functional Unit
SETAC	Society of Environmental Toxicology and Chemistry
REPA	Resource and Environmental Profile Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PEF	Product Environmental Footprint
OEF	Organization Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
OEFSR	Organization Environmental Footprint Sector Rules
CPA	Classification of Products by Activity
AP	Acidification Potential
EP	Eutrophication Potential
GWP	Global Warming Potential
MAETP	Marine Ecotoxicity Potential

1. INTRODUCTION

1.1 WORLD AQUACULTURE

Over the last 20 years, the aquaculture sector has increased its global production from 26% in 2000 to 46% in 2018 (*FAO, 2020*) surpassing fishery industry production. According to the latest FAO report, the world aquaculture industry reached an economic value of $263.6 billion USD and set a record in 2018 with live weight production of more than 114.5 million tonnes. Almost half of this annual production was finfish (47%), followed closely by molluscs with a production of 17.7 million tonnes per year, dominated by bivalves (9.4 million tonnes), as shown in Table 1. Currently Asia dominates the aquaculture market for both inland and marine/coastal farming, outpacing American and European products. European aquaculture production amounts to 3 million tonnes per year, of which 1/3 is represented by farmed mussels.

Table 1: Aquaculture statistics (FAO, 2020)

Production	tonnes
World production	
fishery and aquaculture production	178.5 million
aquaculture production	114.5 million
farmed bivalves	9.4 million
farmed mussels	2 million
Europe production	
aquaculture production	3 million
mussel production	1 million
Italy production	
aquaculture production	143.3
bivalve production	93.2
mussel production	38.75

In Europe, the largest producers of aquaculture goods are Spain and France. Italy is the third largest producer of aquaculture products with an annual production of 143000 tonnes per year. Italian aquaculture produces significant quantities of bivalves, around 65% of the total amount. The main farmed species are cupped oysters (*Crassostrea spp*), carpet shells (*Riditapes phioloppinarum*), scallops (*Pectinidae)* and sea mussels (*Mytilidae*). Among these, mussel production accounts for 40% of bivalve production, meaning an annual output of 39 tonnes (*FAO, 2020*).

1.2 MUSSEL FARMING IN VENETO

In the Veneto region, mussels have a yearly production of 15500 tonnes with a turnover of 100 million of euros and around 4000 employees in the sector (*Boffo et al., 2019*). As the data suggest, Veneto is one of the most common regions for mussel farming, thanks to rapid development in this sector dating back to the early 20th century (*Osservatorio socio-economico della pesca e dell'acquacoltura, 2014*).

In this region, mussel farming methods differ depending on the type of production, either coastal or marine. Marine production occurs on offshore farms, which use the long-lines method where mussels hung from a rope and starting at a depth of 3-5 meters to avoid turbulences cause by waves. To keep mussels in position, farmers use plastic nets called "socks" which have different mesh size depending on the size of the organisms. Socks are changed from time to time as the organisms grow until they are ready for harvesting. Longlines are anchored on the seafloor and can be identified from the surface thanks to buoys, which keep the ropes floating in the water column (Fig. 1).

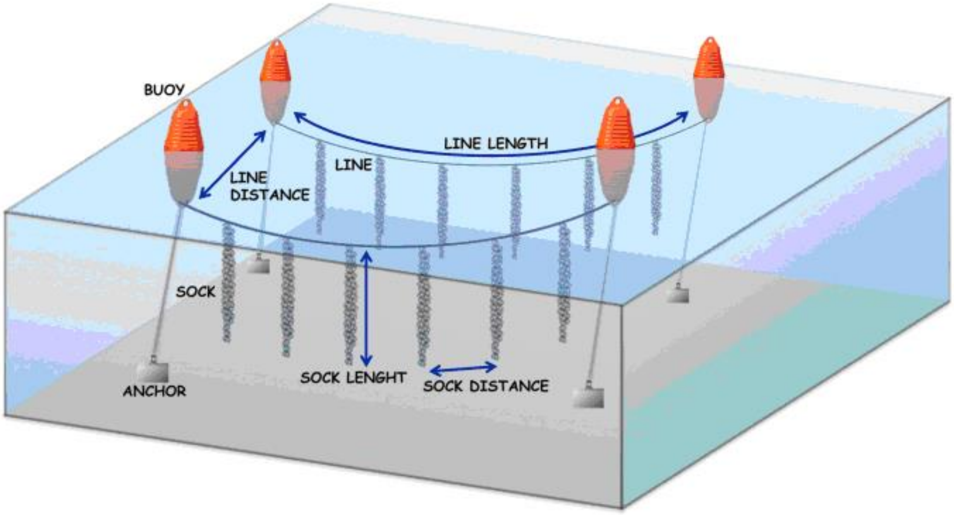


Figure 1: Offshore longlines mussel farm (Caroppo et al., 2012)

On the other hand, mussel farms located in coastal areas are specifically designed for shallow waters (depths of 5-10 meters). In this case, mussels are farmed on tubular nets which are hung on vertical poles, usually made of wood, placed at a regular distance (Fig 2).

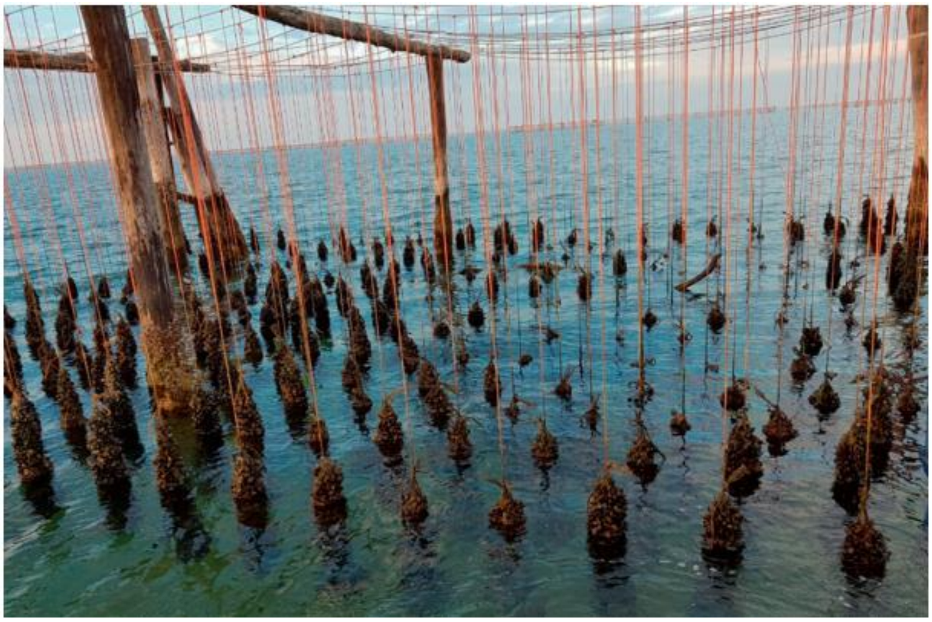


Figure 2: Mussel farm in coastal areas (Boffo et al., 2019)

As the production of mussels is destined for human consumption, it is necessary a specific legislation certifying the quality of the product in order to avoid health risks. The D.L. 530/92 legislation establishes the hygienic-sanitary norms applicable to the production and marketing of live bivalve molluscs (both mussels and other shellfish), whereas the D.L. 531/92 is applied to the fishing industry. These decrees are supported by EU regulations (Reg. CE n. 852/2004, Reg. CE n. 853/2004, Reg. CE n. 854/2004) which broaden the subject in order to provide greater guarantees of health and food safety for products. Of a particular importance, in the Reg. CE n.854/2004 is present the classification of production areas of bivalves based on the level of seawater contamination. The presence of contaminated water by pathogens or chemical pollutants could be harmful to the filtrating feeders and consequently could be affecting the health of the human consumer. For this reason, seawater of the mussel breeding site must be tested and classified based on its quality in one of the three zones identified by legislation. Each area requires different treatment of the product before human consumption:

- “A” zone: areas where the quality of water allows the farmed molluscs to be directly packed and distributed after harvesting. These are usually found in marine settings.
- “B” zone: areas with a suboptimal water quality. In these areas, bivalves can still be farmed but must undergo a depuration or relaying process before being sold for consumption. The difference is that the depuration is carried out in an inland facility, while relaying is a natural depuration that occurs in open sea. Usually, these zones are located where there is a little water exchange.

- "C" zone: areas where molluscs cannot be farmed because of the health risk posed by these waters. However, mussel' seeds can be harvested from these zones and transported to an "A" or "B" zone to be farmed (*Osservatorio Socio Economico della Pesca e dell'Acquacoltura, 2014*).

In Veneto, 33% of aquaculture companies practice only offshore mussel farming, while the rest have other activities, such as small-scale fishing, mussel farming in lagoons through fixed pole method or the cultivation of other bivalves (mainly oysters and clams), carrying out the depuration processes where required.

The primary mussel farmed in the Veneto region, as well as in the rest of Italy, is *Mytilus galloprovincialis,* a Mediterranean bivalve mollusc with an elongated shape. The shells are oval and have black or purple coloration on the outside and mother-of-pearl shades on the inside. Mussel colour differs based on sex: females are orange-red, and males are creamy yellow. They are filter feeders and live anchored to submerged rocks by filaments called byssus.

1.3 ENVIRONMENTAL IMPORTANCE OF MUSSEL FARMING

Due to a low production cost and high nutritional value as a protein source, in Italy as well as in the rest of the world, mussel production has rapid developed over the years. Despite the vast depth of knowledge in this industry, it is still widely researched. The most recent studies focus on the importance of mussel production tackling the growing problem of climate change.

The climate change is mainly caused by the emissions of carbon dioxide and other greenhouse gases (GHGs) in the atmosphere, generated by anthropogenic activities. These gases cause the "greenhouse effect", that leads solar radiation to fail to escape from the Earth's atmosphere, consequently causing a global warming of the planet climate. According to the latest IPCC report (2022), the global food system is contributing 25-30% of the total GHGs emissions. In particular, the livestock sector accounts for 18% of the total emissions (*FAO, 2006*). In 2018, the UN Food and Agriculture Organization (FAO), reported that livestock farms on European soil were responsible for the emission of 502m tonnes of carbon dioxide per year, more that the GHGs emitted by cars (*Harvey, 2020*). Meanwhile the global emissions of the food from animal origin are estimated to be 7.1 Gt CO_2 equivalent per year (*Gerber et al., 2013*). For this reason, it is essential to find an alternative protein source with lower GHGs emissions.

From a nutritional point of view, mussels are a valuable protein source, that can be implemented instead of red meat production. In fact, each kJ of mussels has about the same protein level contained in beef: in 600 kJ of beef there are 24 grams of protein whereas in the same amount of mussels there are 22 grams (*Yaghubi et al., 2021*). In addition, mussels contain essential amino acids (EAA) in the proper proportion to get a healthy and balanced diet, they are a rich source of vitamins and contain good amounts of minerals *(Chi et al., 2012*).

According to several previous LCA studies, the environmental performance of mussel production has been proven to be better compared to the beef one. As shown by Roberts et al. (*2015*) mussels are considered more sustainable not only for their potential to ease effects of global climate change, but also for land and water use. Considering livestock production consumes approximately 8% of the global water supply (*Schlink et al,* 2010), bivalve production requiring the least amount of freshwater is particularly promising (*Verdegem et al, 2006*).

Moreover, mussels can contribute to reducing the atmospheric GHGs and improve the environment's ability to absorb carbon dioxide. To do this, mussels and other bivalves act like bio-pumps in lagoon and shallow water: they absorb CO_2 on the water surface reducing its concentration and causing a transfer of atmospheric carbon dioxide in seawater (*Tang et al., 2011*). This is not always true for all bivalves in different geographical regions. As stated by Bertolini et al. (*2021*), in the Venetian lagoon clam's absorption ability is influenced by seasonality: they work as source of CO_2 in summer and as a sink in winter. This behaviour might also apply to the thesis' mussels, since the analysed company is located in the aforementioned lagoon.

Mussels' shells could also contribute to the absorption of CO_2. Being made of more than 90% of $CaCO_3$, shells have the potential to sequester 5-7 million metric tons of CO_2 per year (*Alonso et al., 2021*). However, burning the shells release the absorbed CO_2. To avoid this, shells can be used in other, more sustainable ways. Some of the most studied uses of mollusc's shells are as a livestock supplement in the poultry industry (*Moris et al., 2019*), as a bio-substitute of ground calcium carbonate (GCC), limestone in the glass industry (*Teixeira et al., 2017*) and many others.

Mussel industry can also promote some other ecosystem services, such as the reduction of eutrophication in coastal waters. This phenomenon is caused by an excess of nutrients, such as nitrogen and phosphorus, in the marine environment. The consequence is a rapid and uncontrolled growth of algae whose decomposition consumes large quantities of oxygen making the water anoxic, an unliveable condition for aerobic organisms. Mussels, like other bivalves, are filtering feeders, which means they absorb dissolved organic particulates, which contain nutrients. These nutrients are then stored in mussel's tissues, which are 1.4% nitrogen and 0.14% phosphorus (*Kaspar et al. 1985*, *Rose et al., 2015*). In this way, they reduce the concentration of phytoplankton, preventing the eutrophication process and increasing water transparency by assimilating the suspended particulate matter (*Lindahl, 2005*). Thus, they help protecting endangered species and fragile habitats. Similarly, mussels and bivalves play an important role in the ecosystem food-webs. They are an essential link between the organisms in water column and benthonic communities, as a small part of the nutrients absorbed are converted in mussel faeces. This makes the faeces a great substrate for the proliferation of denitrifying bacteria, organisms which helps mineralisation of nutrients and closure of the nitrogen cycle (*Rose et al, 2015*).

Furthermore, the mussel's industry does not require a lot of human intervention because mussels are organisms that feed through the filtration of water, so farming implants do not require additional chemicals or supplemental nutrients. The production chain in mussel farming companies can also be improved in a circular economy approach. As seen before, mussels have a well-balanced amino acid profile; as such the organic waste (damaged or dead mussels) could potentially be used for animal feed or sold as fertilizer (*Lindahl, 2013*). Obviously to upgrade the circularity of the business a cost-benefit analysis must be conducted to verify the economic feasibility. It must be kept in mind that this improvement will rise the costs of the processing of organic waste, but it will also reduce the cost of the disposal and produce new income on a different final product. Some studies made by Berge and Austreng (1989) proved that mussels can be used as fish feed, even though a large percentage of blue mussels is not ideal.

2. AIM OF THE STUDY

The goal of the thesis is to investigate the environmental footprint of a mussel farm located in the Southern Venetian lagoon. The environmental footprint has been carried out using the Life Cycle Assessment, a standardized and analytical methodology to examine, in detail, the potential impacts on the environment. The results are an accurate presentation of the environmental sustainability of the farm, which could lead to the identification of the processes that mostly affect the environment and, therefore, support a company in enhancing its environmental sustainability. Moreover, the comparison with other studies or benchmarks could suggest alternative management strategies to improve the environmental performance.

The sustainability analysis has been applied to a mussel farm located in a “B” zone, where the production process requires depuration procedures before the distribution of the final product, as stated in the European legislation Reg. CE n.854/2004. Whereas other LCA studies on mussel farms focus on “A” zone farms, in which harvested mussels are directly packed and distributed. Therefore, it is essential to conduct a comparison between the two production processes to evaluate the difference in the distribution of the potential impacts.

3. CASE STUDY: MUSSEL FARM

The mussel farm is located in Chioggia, in the Northern part of Italy facing the Venetian lagoon on one side and the Adriatic Sea on the other (Fig. 3).

Figure 3: the location of the facility (Wikipedia), the mussel farm and the depuration facility (Blupesca website)

Specifically, the mussel production analysed was the one of “Blupesca s.r.l.” company. The “Blupesca” company was founded in 1998 and it is a small to medium enterprises with an annual revenue of 10 million euros. It sells wholesale and distributes fresh fishery products:

- fish (anchovy, gurnard, merlano, john dory, sardine, mackerel, sole, weever fish, mullet, red mullet, cepula, cod, Zanchetta, breed),
- molluscs (squid, octopus, musky octopus, cuttlefish, bivalves such as claims, mussels, smooth clams, razor claims, sea truffles, scallops),
- crustaceans (pink shrimp, prawn, red shrimp, squilla).

Most of the products are fished, although mussels (*Mytilus galloprovincialis*) and clams (*Tapes philippinarum*) could also be farmed. The mussel farm of the Blupesca company is located in a “B zone”, which, based on Reg. CE n.854/2004, requires a depuration process before the distribution of the final product. The thesis has only assessed the mussel production.

The Fig. 4 shows the phases of the mussel supply chain.

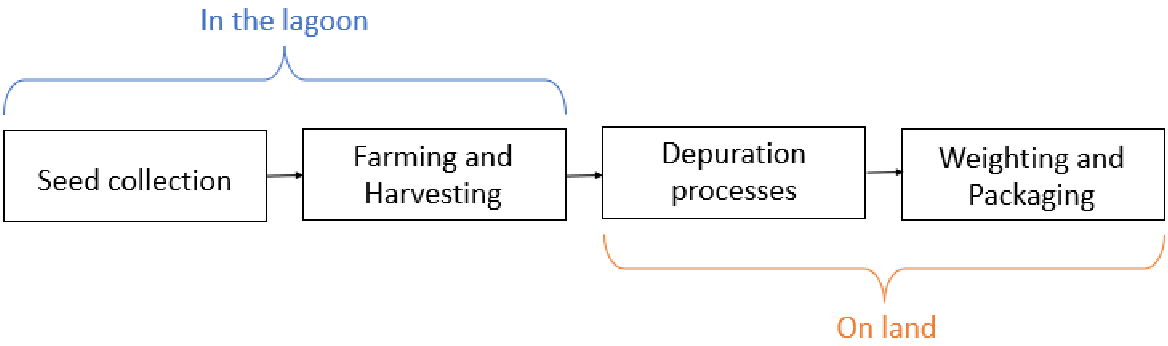


Figure 4: Phases of mussel production

In the first phase of the mussel supply chain mussel seeds are collected and transported in the mussel farm. Depending on the season the mussel seeds have different origin: from late November to the end of February already-grown mussels are imported with regular certification from Galicia (Spain) while the rest of the year the farmed mussels are Italians. The imported mussels are already the right size to be sold, so they will be allocated in the farming plant for only a month to heal the stress caused by the transport and to increase the quality aspects of the product. After this period the Spanish product is depurated, packed, and distributed. While Italian mussels are collected as seeds, and they take around a year to grow. In the thesis has only been assessed the supply chain of Italian mussels because, in order to consider also the Spanish production, it would have been necessary to estimate the impacts of the Spanish mussel farm.

The mussel farm is located in the shallow water of the Venetian lagoon, and it is characterized by wooden poles as brackets for the steel ropes. Mussels are hung on ropes through plastic nets, which keep them in position. The plastic nets are called “socks” and during the growing period they are changed with bigger mesh size at least three times in order to rearrange the distribution of mussels. This procedure is essential to avoid an excessive density of mussels on poles, which could lead to the death of smaller organisms that cannot filtrate nutrients. Once they reach the commercial size (at least 5 cm), mussels are harvested and landed by boat with a document of registration (DDR), that report the quantity harvested, the area where were collected, the health status and the destination (*Boffo et al., 2019*).

The land facility is divided in two parts: mussels are depurated for approximately 8-12 hours in the first area, subsequently weighted and packed in the second one. In Fig. 5 the main steps of the two phases are summarized.

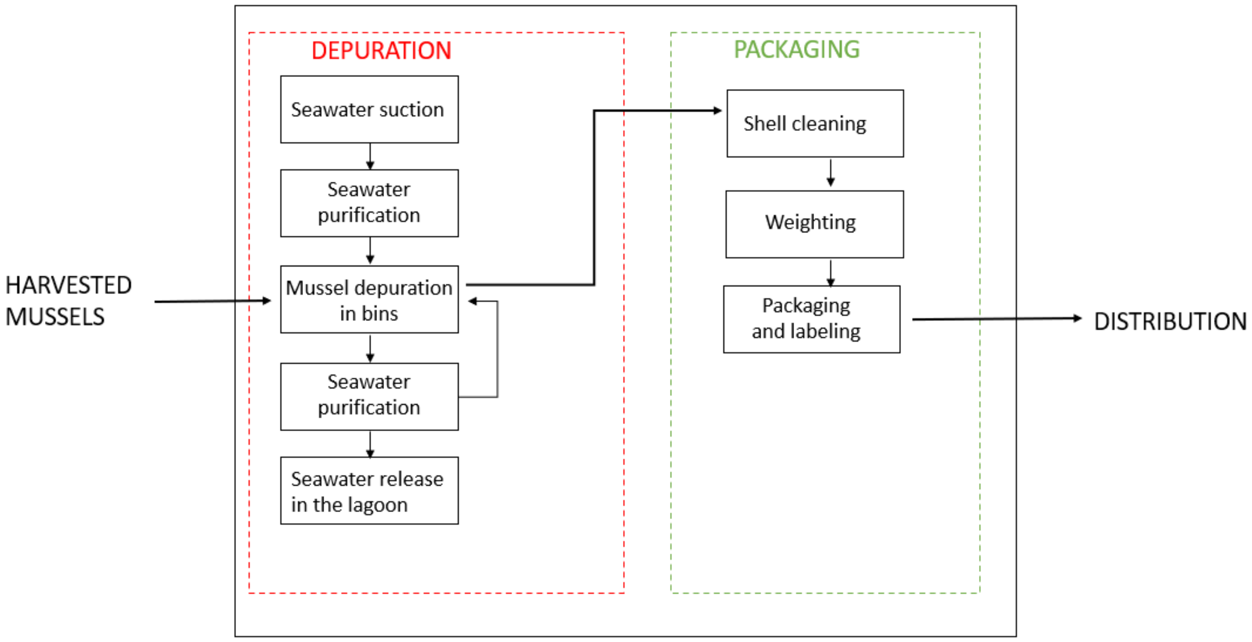


Figure 5: The two phases of the land facility

The depuration plant works as a semi-closed system because part of seawater is lost. Seawater is pumped from the nearby lagoon, purified, used for the mussel depuration, and replaced after 10 days with freshly seawater. The water suction and purification system start with a submergible pump and a mechanical drum filter with automatic backwash, that avoid the passage of solids. After this first filtration, water is kept in a water tank before it is purified from microorganisms through a 6 UV lamps system. The decontaminated water is finally channelled to the depuration plant.

The depuration process takes places in a series of 21 HDPE tanks, called “bins”, arranged linearly one after the other (seven columns) and with a vertical development in height (a maximum of three bins superimposed). In these bins from the upper pipes, through the “showers”, falls clean seawater. They also contain a plastic grid on the bottom where could lay for depuration up to 250-300 kg of mussels, avoiding the contact with the organic wastes that comes out from the depuration process. Mussels are left in the bins with current seawater for 8-12 hours, depending on the weather condition of the previous days. For example, if there has been a swell or a heavy storm, the duration of the process is increased up to 12 hours because the excess of rainwater causes the nearby civil sewage plant to directly dump the untreated water in the lagoon. This increases the likelihood of a contamination from Norovirus, so mussels have to be held in bins for longer to expel the pathogen. Afterwards seawater and mussels take two different paths: mussels are transported to the packaging area, while the water must be sanitized again to be re-used in the circuit. Seawater is taken through biofilters and sand filters, which reduce the nitrates and ammonia from the water. These filters are composed by lime sand and algae namely, *Lithothamnium calcareum*. Afterwards the water is channelled to a skimmer, that has a dual function: on one hand it filters and clarifies water to eliminate organic wastes and foams, while on the other hand increases the oxygen concentration: this last process is key, because during the previous depuration cycle mussels consumed oxygen. In the blast chiller, the water is then cooled to keep the temperature between 13°C and 16°C. Maintaining the temperature in this range is essential because mussel's filtration rate is highest at 13°C. However, it is also important to avoid large changes in temperature between the water in the inner circuit and the seawater. For this reason, during summer temperature is kept a little bit higher than the range, sacrificing a fast depuration to have a good quality product. As done for the water pumped from the lagoon, also this water must undergo a disinfection procedure to eliminate most pathogens (algae, bacteria, and viruses). At the end of the sterilization process, the water is stored in two water tanks until it's used again for depuration purposes.

The depurated mussels are then carried in the second section, where they are weighted, packed, and prepared for shipment and distribution. The machineries used are a hopper with loading belt to carry the product in the brushing machine, where shells are cleaned. Afterwards through a sorting belt, damaged or already dead mussels are manually eliminated. This waste has to be collected by a special company, that handles category 3 by-products. Compared to the annual production of mussel (100800 kg), around 29000 kg are waste, i.e., almost 30% are wasted. After the selection a hopper with unloading belt carries the final product to an automatic weighing and packaging belt. Last, plastic nets are closed through a manual clipping machine, and labels are added. Labels contain information of the origin of the product, the weight, the disposal procedures for clips, labels, and nets and the instructions on how to properly preserve and cook the product. In some cases, before the packaging can be used a debysser, a machine that removes the mussel's byssus. If this procedure is applied the product must be consumed in a short time and it is usually used if selling already cooked mussels.

4. MATERIALS AND METHODS

4.1 LITERATURE BACKGROUND

To achieve the objective of this research, first it is essential to carry out a literature review to understand the background and the state research in the field. The bibliographic research was carried out using “Research gate” and “Google Scholar” platforms. Firstly, LCA studies on the aquaculture sector were investigated and afterwards the research was narrowed to LCA studies on mussel farms. The keywords used were “LCA” (and “life cycle assessment”), “aquaculture”, “mussels” and “mussel farming”. The time frame is 20 years, so the publications were written between the early 2000s and the present day.

When the LCA methodology was firstly developed, it was mainly used to assess the sustainability of agricultural and industrial sectors. The aquaculture field was included much later: first assessments began in the early 2000s focusing on products such as Swedish cod (*Ziegler et al. 2003*), Danish fish products (*Thrane, 2004*), Spanish tuna (*Hospido et al., 2005*) and Norwegian cod (*Ellingsen et al., 2006*). Thanks to the growing interest in creating sustainable businesses and aquaculture industry’s “green” reputation, the use of a Life Cycle approach to study the seafood production increased rapidly (*Pelletier et al. 2007*).

One of the first reviews on the topic, by Cao et al. (2013), sought to compare a dozen different studies that applied LCA to aquaculture facilities. In order to get an accurate comparison, the LCAs were re-calculated using the same functional unit and same impact categories. The results of the comparison lead to the discovery of an important limitation of the methodology: the life cycle approach was able to calculate the global impact, but the regional effects on the habitats and biodiversity were underdeveloped. Following that research, a series of aquaculture techniques to increase sustainability were investigated to promote the industry’s development. A similar review comparing LCAs by Bohnes (2019) analysed studies published from the prior 15 years and sought to highlight insights, that can be gained by applying LCA to aquaculture systems. A review by Runesson (2021) focused on articles dedicated to a specific branch of aquaculture: blue mussel farming methodologies. The review highlighted the importance of assessing aquaculture, bivalves’ production in particular, as a keystone in food production systems in the future. Moreover, some research using the LCA approach examined the possible positive impacts that mussel production can have on the environment. Some examples have been shown in the previous chapter.

To compare the results of this research to other LCA studies, certain criteria must be taken into account. First, mussel farming studies must focus on a similar production chain to the one being analysed here. With Spain being the largest European producer of mussels, numerous studies conducted a LCA on facilities located in the Hispanic region. For example, Irribarren et al. (2010) analysed the sustainability of both fresh and canned mussels in Galicia (ES). Considering LCA analyses do not highlight regional aspects, it would be most appropriate to utilize studies that focus on the same geographical area. Tamburini et al. (2020) assessed the sustainability of mussel farming in Northern Italy, and Martini et al. (2022) included also analysis of carbon flows, exploring the potential role of biocalcification processes in sequestering carbon from seawater during shell formation. Their results showed shell formation can absorb all the emitted CO_2 during the growth and harvesting processes. However, this measure is dependent on local environmental condition and may not be the same in other climates.

Moreover, Tamburini et al. (2020) assessed an environmental footprint of an offshore mussel farm located in “A” zone, which could be used to compare the sustainability of the two productions.

4.2 LCA METHODOLOGY

The Life Cycle Assessment is a standardized methodology to analyse the environmental impacts generated by the entire life cycle of a product or an activity, starting from extraction of raw materials and ending with the disposal of a product as a waste. The concept of LCA was firstly developed in the late 1960s in the U.S.A, when the concern for the protection of the environment started spreading (*Bjørn, 2018*). In the 1980s REPA (Resource and Environmental Profile Analysis) created the first proto-LCA procedure characterized by life cycle inventory (LCI) but lacking a proper LCIA (life cycle impact assessment). This phase was added a decade later by SETAC (Society of Environmental Toxicology and Chemistry) both in North America and Europe. This agency is considered the first to develop the complete LCA methodology (*Klöpffer, 2006*). This framework was then standardized by the ISO (International Standards Organization) in the late 1990s and it is subject to continuous updates from year to year. Using a standard procedure to conduct an LCA assures credibility and allows comparison of studies from different regions of the world.

LCA is currently regulated mainly by the ISO 14040 “*Environmental Management—Life Cycle Assessment—Principles and Framework*” and ISO 14044 “*Environmental Management – Life Cycle Assessment – requirements and guidelines*”, which provide both theoretical concepts and practical indications to perform a correct study of the environmental performance of a product or service (*ISO, 2006*). Because of the recognition of the importance of this methodology, the European Community have created a specific platform called “EPLCA” (European Platform on Life Cycle Assessment) that aims to promote life cycle thinking in business and in policy. It focuses both on the methodological needs essential to use properly the LCA tool and on the implementation and improvements of LCA practices (*Sanfelix et al., 2013*).

An LCA study includes 4 stages (*ISO, 2006*):

1. Goal and scope definition,
2. Inventory analysis,
3. Impacts assessment,
4. Interpretation.

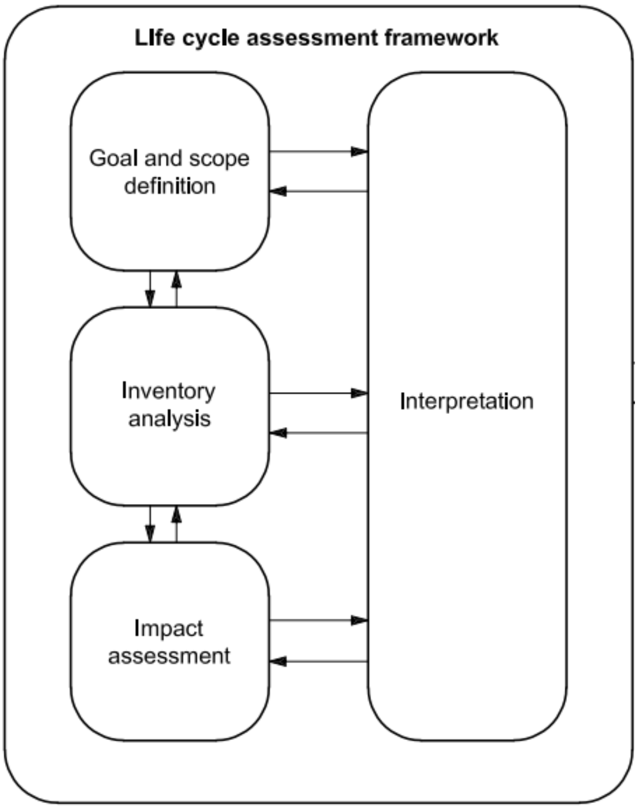


Figure 6: Stages of an LCA (ISO, 2006)

As shown in Fig. 6, LCA stages are not all consequent but the definition of one stage may have a direct influence on the previous one. For this reason, the life cycle assessment is considered an iterative procedure, where initially decided parameters can be modified while developing the analysis. In particular, the interpretation process can lead to review the whole analysis, or to change the original goal. This could lead to the use of LCA as a creator of scenarios: various scenarios are elaborated based on the different parameters, afterwards one scenario could be chosen as the most reliable for providing a correct estimate of the sustainability of the product (*Krozer et al, 1998*).

4.2.1 GOAL AND SCOPE DEFINITION

This phase focuses on the identification of the aim of the study and details on the procedures necessary to carry out the analysis. It includes the definition of the system boundary, that represents the limits within the production chain has been analysed. The system boundary defines the unit processes to be included in the system, therefore, some inputs or outputs can be excluded if not relevant. This process is called “cut-off” and ISO guidelines indicated the necessary actions to undertake the selecting process, that is however difficult to put in practice (*Suh et al., 2004*). The system boundaries should be established also considering the original goal of the study and the available data. Once defined the system boundaries it can be identified the type of LCA study:

- “Cradle-to-grave”: the LCA starts with raw materials extraction and ends with the product disposal as a waste.
- “Cradle-to-gate”: the study still begins obtaining raw materials but stops at the end of the manufacturing process when it can be labelled as a final product. Therefore, the distribution, consumption/use and the disposal are not considered.
- “Cradle-to-cradle”: a specific type of LCA that applies to products that are re-used or modified to create new products in a circular economy perspective. It starts at the production of the main product, and it ends with the beginning of the manufacturing of the second product.
- “Gate-to-gate”: if the analysis takes in account only of the manufacturing process.

Within the Goal&Scope, the FU should also be defined. The FU provides the reference unit to which all the other values are normalized. The choice of functional unit should made taking into account the scale of the study and the possibility of comparing the results with those of similar studies. Ideally the FU should be chosen based on the function of the product rather than the physical object.

For example, in nutritional studies, it may be more appropriate to select as FU the caloric of the protein content of a given food item, rather than the mass unit (*Weidema et al., 2004*).

4.2.2 LIFE CYCLE INVENTORY

The second phase of an LCA procedure is the inventory, that consists in the data collection. At this stage collaboration between the company and the LCA practitioner is essential, because the more detailed are the provided information, the more accurate will be the outcome of the analysis. Moreover, the data should be collected in an iterative process since, as the data comes in, more is learned about the production chain (*ISO, 2006*). For this reason, the LCI is considered the most time-consuming phase. The gathered data represent the elementary flows, so are mainly raw materials and energies as input while the outputs are product, coproducts, wastes and emissions to the surrounding environmental compartments (*ISO, 2006*). Both features could be from nature or of anthropogenic origin. During the collection phase, it is also possible to include a flow diagram, that helps both understanding the processes inside the system and developing a checklist of all the data required (*Hetherington et al., 2014*). It is likely that companies may not be able to provide all the data requested by the LCA analyst. This lack of data can be solved either by making some assumptions, based on an in-depth bibliographic research on similar studies, or creating the data through empirical calculations (*Zargar et al., 2022*). Once the data have been gathered, input of matter and energy are normalized with respect to the FU.

Industries often produce multiple final products, and the production chain may not be linear. In this case, according to ISO 14044 guidelines, the system can be expanded based on availability of the data concerning the coproducts. If the system expansion is not doable, one should proceed with the “allocation” process, where the production inputs and outputs are partitioned between the coproducts. Usually, allocation is based on the mass of the coproducts, although sometimes it can also be operated using their economic value. Despite the fact that there is no fixed rule on how to deal with allocation, the method based on the economic value is hardly recommended because of price variation due to market fluctuation. Therefore, it is very important to present the method applied and motivate the choice in order to give the possibility to test the outcome through comparison with other studies, which may have applied different allocation processes (*Vigon et al., 1993*).

4.2.3 LIFE CYCLE IMPACT ASSESSMENT

This phase focuses on calculating the environmental impacts which could be potentially generated by the inputs and outputs included in the inventory. Impacts are related to “categories”, each one being characterized by a category indicator. Usually, these categories are more than a dozen and such a high number can reduce the efficiency of the impacts analysis.

Impact categories also differ based on the LCIA method chosen, which can either be a midpoint or an endpoint approach. These methods give two different level of detail to the analysis: midpoints identify impacts generated by the production early along the cause-effect chain, while endpoints evaluate environmental impacts at the end of the cause-effect chain. Practically, midpoints highlight potential environmental impact generated by an input/output of the system, for example how chemical emissions could affect an environmental compartment, whereas endpoints only show damages on the environmental context as consequence of the previous emissions (*Prè-sustainability, 2021*).

Applying the midpoint approach, the impact categories are the ones listed in the Table 2.

Table 2: Impact categories of the midpoint approach

MIDPOINT APPROACH			
impact category	**indicator**	**unit**	**description**
climate change	GWP	kg CO2 eq	impact generated by emissions of GHGs in a period of 100 years
eutrophication	EP	kg of N and P eq	impact generated by excessive growth of algae due to surplus of nutrients in the water
land use	LUC	m2a	impact generated from the conversion of a natural land in a land used for anthropogenic activities
non-fossil resource depletion	ADP	kg Sb eq	impact generated by consumption of non-fossil resources
fossil resource depletion	ADP	MJ	impact generated by consumption of fossil resources
acidification	AP	kg SO2 eq	quantity of acidic gases emitted to air during the product life

ozone depletion	ODP	kg of CFC-11 eq	impact generated by emitted gases that cause a reduction of the ozone layer. This phenomenon leads to the passage of UV radiations and increase cases of skin cancer
ecotoxicity	ETP	CTUe	impact that damages organisms' health
human toxicity	HTTP	CTUh	impact that damages human health
ionising radiation	IR	Kg U235 eq	impact on human health and natural organisms caused by radiations
photochemical ozone formation	POCP	kg VOC eq	impact generated by emissions of VOC (volatile organic compounds). VOCs in presence of light can create ozone near the terrestrial surface
water depletion	WC	m3	amount of water resources that are been used during the life of a product
particulate matter	PM	kg PM2.5	impact on human health caused by emissions of particulate matter and its precursors.

Based on the scope of the analysis, one can focus on a subset of those listed above and/or introduce other categories, such as the Cumulative Exergy. The most used methods on LCA studies are CML, ReCiPe and the eco-indicator 99 which assess the impact analyses with different sets of categories (Appendix A – *Acero et al, 2016*), different indicators and calculating algorithms.

On the other hand, the endpoints approach identifies impact categories, also called "damage categories", which represent the deteriorated compartment affected at the end of the cause-effect chain. The endpoints are generally the following (*Jolliet et al., 2004*):

- Human health: it is measured as the number of premature deaths, which implies the importance of the cooperation with the World Health Organization (WHO) databases.
- Ecosystem health: its indicator is called "occurrence of species" and it shows how the anthropogenic activities affect the natural balance of an ecosystem, such as a loss of native species or an increase in allotropic organisms.
- Natural resources: the indicator represents the reduction of the possibility for future generation to use a type of natural resource.

Depending on the scope of the LCA, impact assessment phase can be carried out using either midpoints or endpoint approaches. The midpoint method provides a more detailed analysis, while the endpoints display an overall prospective (*Bare et al., 2008).* The LCIA is conducted using software, such as SimaPro, GaBi or OpenLCA. All software have a procedure structured in four main steps (*Klöpffer et al., 1997*):

1. Classification: it establishes a connection between the items of the inventory and impact categories. Naturally one incoming process from the inventory can be linked to more than one category (*Consoli et al., 1993*).

2. Characterization: it quantifies the total contribution of the inputs related to each impact category (*Consoli et al., 1993*).

3. Normalization: based on the ISO guidelines, this procedure is not compulsory unless the PEF standards are applied. This phase involves the multiplication of the entered value with the characterization factor, that is peculiar for each resource and material. This calculation increases the comparability of impacts generated between studies (*EPLCA website, 2013*).

4. Valuation or Weighting (as called by ISO 14040 where this phase is considered optional as shown in Fig. 7): in this last step the previously calculated contribution from the inputs to the impact categories are weighted in order to make a comparison between them. In some case studies, values are grouped to obtain one single overall score of the impact generated by the product (*EPLCA website, 2013 - Consoli et al., 1993).*

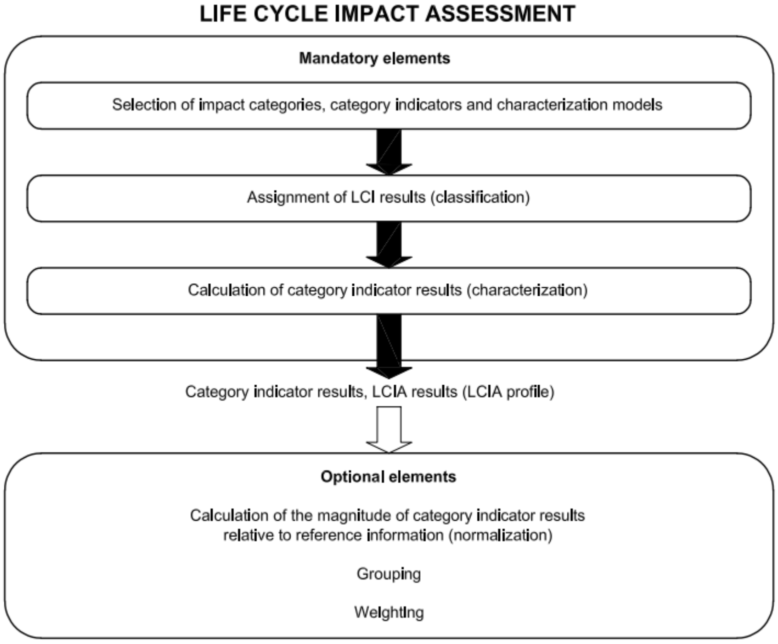


Figure 7: Steps of the LCIA (ISO, 2006)

4.2.4 INTERPRETATION

The interpretation is the final phase of an LCA. Its aim is to process the results and identify the ones that provide significant information with respect to the goal of the study. During this phase, it must be kept in mind that the outcomes are potential impacts and do not necessarily find a response in reality (*ISO, 2006*).

The results can be used for decision-making about the manufacturing strategies of the product, taking into account that the quality of the data directly affect the accuracy of the study. In order to do so, it is important to assess the relevance of assumptions in the overall analysis and, wherever is possible, show the dependency of the outcoming values on the single inputs (*Consoli et al., 1993*).

During the interpretation could also be identified the most impactful activities of the product manufacturing. Therefore, could be suggested improvements on the production chain to implement the sustainability of the company. The suggestions must take into account of their economic feasibility. Wherever the implementations are applied, a new LCA study must be conducted on the implemented supply chain. Thus, the outcomes will be a series of LCA scenarios, from which the one with the least environmental impact will be considered the "best" (*Krozert et al., 1997*).

4.2.5 APPLICATIONS

The LCA framework can be applied in both public and private sectors. The first industrial contexts in which it has been applied were plastics, detergents, and automobiles, followed by the agricultural, mineral and construction sectors. While at the present days the most analysed companies produce energy and biofuels (*Jacquemin et al., 2012*). The LCA methodology was applied in order to evaluate the environmental performance of a product or a service. This way, LCA provides a method to highlight the sustainability of industries, helping the companies managing the environmental footprint of their system. The LCA is not a mandatory framework but can be applied where required by firms.

Although this is the main use, there are further applications. The LCA is commonly applied in the eco-labels sector. In the European context, ecolabels are divided in ecolabels and environmental product declaration (EPD), which both foster the development of sustainable products through the release of a certification to the most virtuous companies (*Breedveld et al.,* *2006*). LCA studies applied to ecolabels certification are regulated by ISO 14020, ISO 14021, and ISO 14025 (*ISO, 2006*). Ecolabels are spreading rapidly as the consumers start to request more environmentally friendly products. Therefore, they are becoming a requirement for companies that want to be competitive in the future market (*Iraldo et al., 2020*).

The ecolabel certification is applied on already-developed production chains, however, LCA procedures can also be used in the eco-design of products, creating from the start more sustainable manufacturing chains (*Breedveld et al., 2006*). In this prospective, LCA helps comparing different scenarios, in which materials and phases are changed in order to identify and develop only the one with low environmental footprint (*Piekarski et al., 2019*).

Other application of the LCA framework equipped with ISO guidelines are the incorporation of the impacts into product standards, that are used as tool for an efficient environmental communication (ISO 14063) or for the quantification and tracking of GHGs emissions. In general, the use of LCA is well-spread in the decision-making context, where generally the approaches are analysing inputs and outputs in order to find the major environmental impacts or study, after a complete life cycle assessment, the consequences of a product production and implement alternatives that could reduce its footprint. (*ISO, 2006*).

Lastly, the LCA approach can also be applied only at some stages of the life of a product rather than from the extraction to the disposal. This technique focuses on the impacts generated by specific parts of the supply chain, consumption or of the waste management. Currently, numerous studies are focusing on waste management issues. This application is widely spread because the waste management represents a primary challenge in the implementation of a circular economy. In order to implement the circularity of a product, it is required an in-depth study of sustainability of inputs and outputs of the system, which can be provided through an LCA (*Christensen et al., 2020*). Overall, LCA studies that analyse specific phases of the manufacturing process (e.g. waste treatment) can be elaborated using the ISO 14044 (*ISO, 2006*).

As it is possible to conduct an LCA only on specific stages of a product life, LCA can also be applied focusing only on one impact category. For example, the “carbon footprint” measures the amount of CO_2 emitted in a product’s life, so basically assessing only the climate change impact category (*Wiedmann et al., 2008*) while the “water footprint” estimates the direct and indirect use of freshwater resources through the water impact indicator (*Hoekstra et al., 2009*).

4.2.6 PRODUCT ENVIRONMENTAL FOOTPRINT (PEF)

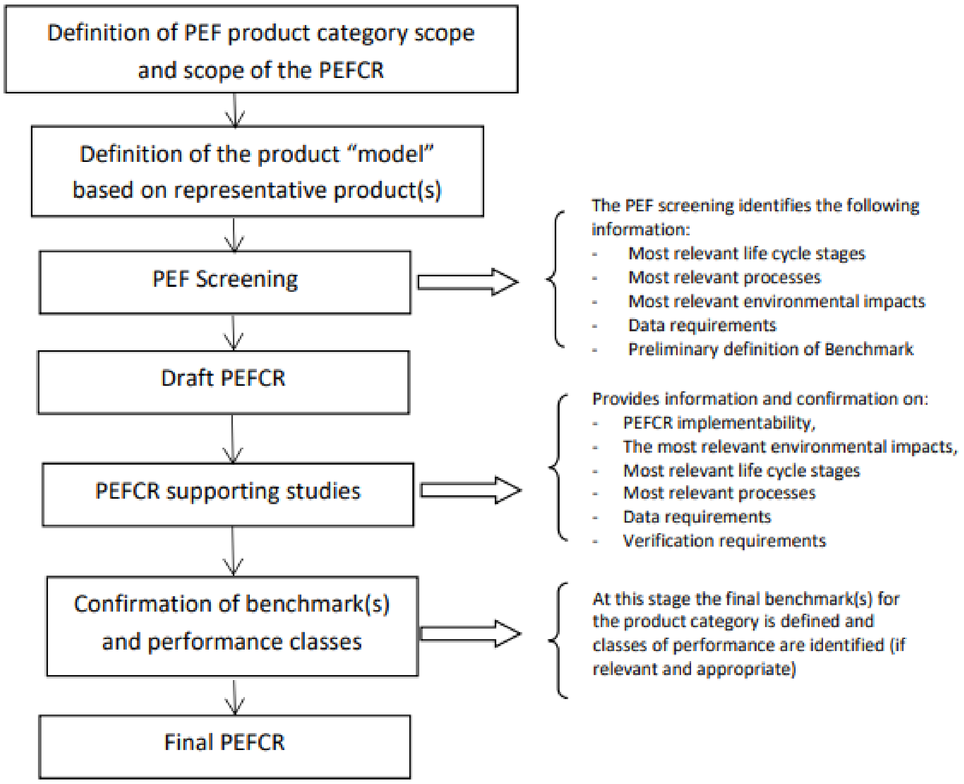
The product environmental footprint (PEF), as well as the OEF (Organization Environmental Footprint), is an LCA-based framework that measures the environmental impacts generated by a specific product or organisation. So, PEF and OEF are used to implement their product sustainability (*EU, 2013*).

These frameworks were firstly developed by the European Commission in 2013 with the aim to make LCA procedure more comparable. Currently, PEF and OEF are undergoing upgrades and further implementations. These frameworks aim to make life cycle analyses of products and organizations more comparable with each other, sacrificing the flexibility of the LCA methodology. However, the concept of "comparability over flexibility" was not accepted without some scepticism (*Finkbeiner, 2014*). Moreover, some industries find the development of these frameworks unnecessary given the existing ecolabel certification methodologies, which aim at the same objective as PEF (*Lehmann et al., 2015)*. For these reasons, the PEF is still an experimental methodology.

PEF aspires to create a specific procedure based on the product class to increase comparability between different analyses of the same product (*Finkbeiner, 2014*). In order to fulfil the scope of the methodology, products are grouped into categories. Each category is defined by the Product Category Rules (PCRs). For the OEF the rules are called OEFSR (Organization Environmental Footprint Sector Rules), however, they are not developed as much as the PEFCRs (Product Environmental Footprint Category Rule). Each PEFCR provides guidelines for performing a sustainability assessment on a specific product in order to get comparable results. Inside the PEFCR are indicated the requirements, characterized by the verb "shall", recommendations defined by the term "should" and finally the optional parts added with the expression "may".

In order to get a high comparability, each PEFCR includes a defined list of the mandatory processes to assess for a specific product and a list of the 16 impact categories that are essential to assess the environmental footprint (*European Commission,* 2018). Impact categories can differ depending on the product assessed. Products are classified based on the CPA (Classification of Products by Activity), that uses codes to identify which products are included in a specific PEFCR (*European Commission, 2018*).

The procedure to develop PEFCRs, reported in Fig. 8, is carried out by an assembly of volunteering stakeholders. As can be seen, it takes at least 6 stages before having a final draft, that means the procedure is quite time-consuming (*European Commission,* 2018). For this reason, up to now, PEFCR are available only for the following products categories: beer, dairy, decorative paint, detergents, pipe systems, intermediate paper products, animal feed, IT equipment, leather, metal sheet, packed water, pasta, pet food, photovoltaic energy production, rechargeable batteries, T-shirts, thermal insulation, uninterrupted power supply and wine. OEFSRs were approved only for copper production companies and retail businesses (*europa.eu, 2021*).



The PEF screening identifies the following information:
- Most relevant life cycle stages
- Most relevant processes
- Most relevant environmental impacts
- Data requirements
- Preliminary definition of Benchmark

Provides information and confirmation on:
- PEFCR implementability,
- The most relevant environmental impacts,
- Most relevant life cycle stages
- Most relevant processes
- Data requirements
- Verification requirements

At this stage the final benchmark(s) for the product category is defined and classes of performance are identified (if relevant and appropriate)

Figure 8: Steps for the development of a PEFCR (European Commission, 2018)

A PEFCR assessment presents strong similarities with an LCA one: (*europa.eu, 2021*):

1. EF goal and scope definition,
2. EF inventory analysis,
3. Impact Assessment,
4. Interpretation and Reporting,
5. Verification and Validation.

The first four phases mirror those described in section 4.2, while the last one consists in a review of the conducted analysis in order to verify that the minimum requirements have been met. It is usually applied when the PEF procedure is used for external reporting (*europa.eu, 2021*).

It was not possible to estimate the PEF for the case study presented in this thesis, as the framework for "marine fish" as a product is still a draft and undergoing the pilot phase. Moreover, the draft does not include marine aquaculture products.

4.3 LCA OF THE CASE STUDY

4.3.1 SCOPE AND GOAL DEFINITION

As previously stated, the scope of the study is to apply an LCA for assessing the environmental sustainability of mussels produced in a B area, which includes three steps:

1. a grow-out in a licensed area,
2. depuration,
3. packaging.

The goal is to increase the awareness of the company about its environmental footprint and potential impact "hotspots". In this way, it may be able to reduce it by improving the production line appropriately. Moreover, a comparison with the environmental footprint of an offshore mussel farm has been carried out in order to assess the different methods of mussel farming.

Although the ISO guidelines suggest using a functional unit related to the role of the product instead of a physical feature, similar studies were almost always conducted using a functional unit related to the mass, usually 1 tonne or 1 kg of fresh mussels. For this reason, the functional unit chosen is 1 kg of live weight depurated mussels (*Mytilus galloprovincialis*) as a final product ready for consumption in accordance with most bivalves LCA studies (*Iribarren et al, 2010, Runesson, 2021*).

Regarding the system boundaries, it was decided to conduct a cradle-to-gate LCA. The system assessed, represented in Fig. 9, starts with the seed collection and finish at the end of the weighting and packaging procedures before the distribution. Moreover, the lifetime of the facility was considered to be around 20 years.

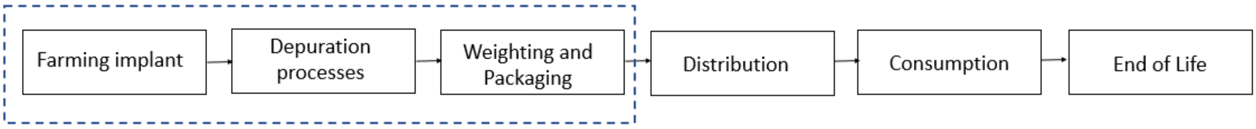


Figure 9: System boundaries

4.3.2 INVENTORY

Before conducting the data collection for the inventory, it was essential to study the system. Thanks to a guided tour of the company's facility by Doctor Luciano Boffo, it was possible to create a diagram that summarizes the main inputs and outputs of the process (Fig. 10).

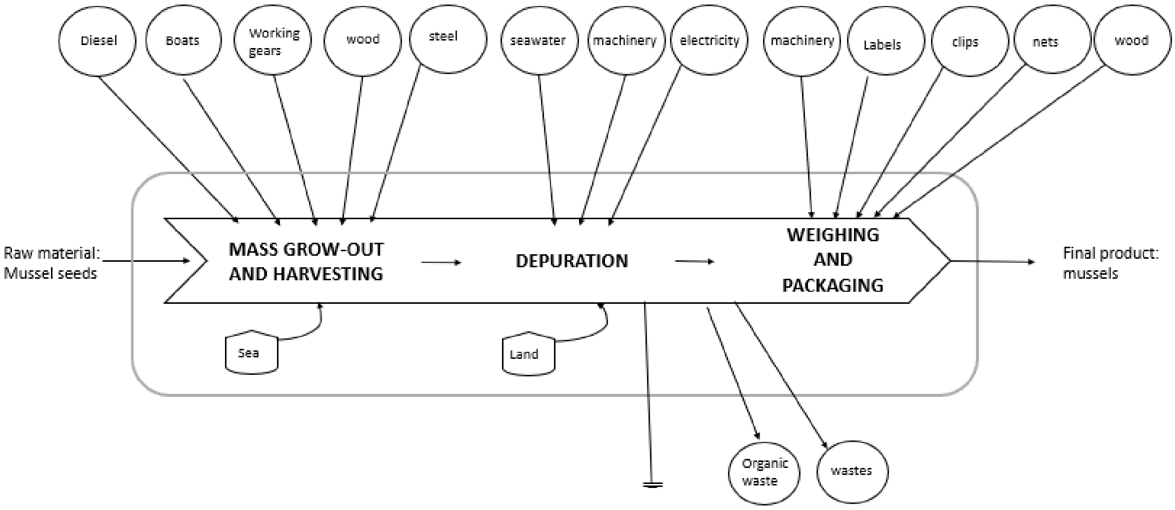


Figure 10: System diagram

Thanks to the cooperation with the Blupesca company, it was possible to collect a fair amount of data, which allowed the creation of a detailed inventory of the system (Table 3). A more comprehensive version of the inventory can be found in Appendix B. The values shown below are standardized with respect to the functional unit, i.e., 1 kg of live weight depurated mussels.

Table 3: inventory for 1 kg of live weight mussels

ITEM	QUANTITY	UNIT
INFRASTRUCTURE		
land occupation	0.00010101	m2a
sea occupation	0.00451687	m2a
boat hull	0.00019841	kg
ropes	0.00112484	kg
wooden poles	0.00022434	m3
bins	0.00012388	kg

ITEM	QUANTITY	UNIT
MACHINERY		
on boats		
boat engine	0.00000142	p
generator	0.00000050	p
water capture		
submersible pump	0.00000083	p
pipes for water transportation	0.00000014	kg
depuration systems		
Skimmer	0.00002626	kg
UV lamps	0.00000808	p
Sand bio filters	0.00060606	kg
Chiller	0.00000016	p
weighting and packaging		
water tanks	0.00005495	kg
brushing machine	0.00023810	kg
hopper with conveyor belt and automatic weighting	0.00059524	kg
debysser	0.00005952	kg
conveyor belt	0.00000103	m
manual clipper	0.00003175	kg
platform scale	0.00000606	kg
classical scale	0.00000081	kg
CONSUMABLES		
socks	0.01	kg
clips	0.00148810	kg
labels	0.00019607	kg
pallets	0.01587302	p
plastic nets	0.05952381	kg
working gears	0.00010119	kg
seawater	0.00221212	m3
ENERGY		
Electricity for machinery	0.22222222	kWh
Gasoline boat	0.00396573	kg
Gas for generator	0.00347222	kg
motor oil	0.00004132	kg
OUTPUT		
organic waste	0.03244048	kg

Assumptions

Most data concerning mussel farm, consumables and energies were primary data, while a few others required some assumptions, mainly machineries and tubular nets called “socks”.

The company provided the number of machineries which operates mainly in the land facility. However, most of these technologies (except the submergible pump, the chiller, and the UV lamps) are specific for the mussel production and processing. For this reason, it was impossible to find a corresponding process in the Ecoinvent database. After some investigations, it was decided to proceed using the material and the mass for each machinery. Most of machineries are made of stainless steel and, researching retailers selling this type of equipment, it was possible to estimate the weight of most pieces of equipment (*teammare.it – cocci.it*). In some cases, it was necessary to undergo some calculation in order to find the mass of the machines and this may have led to an increase in the error of the estimation. Moreover, only considering the main material of which machinery are made, the impact generated by the production process of the machinery was excluded. In some rare case, it was not possible to find information about machineries, therefore some were excluded from the inventory namely, the drum filter used in the water suction phase, thermometers used to measure seawater temperature during the purification process and mechanical filters used to disinfect seawater before it could be running back into the circuit. The impossibility of entering these data could lead to a small underestimation of the impacts.

Another relevant assumption is the quantity of tubular nets called "socks" used. Although the company provided the material of the "socks", they were not able to provide any additional information on the amount of nets used yearly. For this reason, it was necessary to estimate the input through web research. It was decided to consider 1 m of net for each kg of mussels sold on the market (*lanuovaecologia.it*), that has an average weight of 10 grams (*intermas.com*).

Lastly, fuels required a conversion of the unit of measurement from volume to mass using the density. This conversion should not cause any error in the calculation of impacts.

Allocation

Since the company depurates other bivalves (mainly clams) using the same equipment, it was required an allocation process on the machineries and their energy consumption. In accordance with the literature (*Svanes et al., 2011*) the allocation by mass was selected, which is independent on the variability of the market price. The total masses of shellfish entering and exiting the system are listed in Table 4.

Table 4: final products and coproducts of the Blupesca facility

FINAL PRODUCTS	**quantity**	**unit**
total depurated bivalves	495500	kg
total annual mussel production	100800	kg
annual production of Spanish mussels	89900	kg
annual production of Italian mussels	10900	kg
total mussels disposed as waste	29000	kg
Italian mussels disposed as waste	3270	kg

The annual mussel production data considers both the Spanish and Italian mussels; however, it was only assessed the Italian production because there is no information on the impact of the Spanish mussel production. In order to do so, the annual values where firstly divided for the total mussel production and afterwards multiplied for the Italian production. Once the data were referenced to the annual Italian production, they were normalized to the FU.

The allocation was applied to the machineries and their related electricity input as they are used both for mussels and clams, while the consumables and infrastructure did not need any allocation.

Waste management

Waste treatment and waste scenarios were modelled for consumables. However, packaging materials (clips, plastic nets, pallets, and labels) were not considered as they are not disposed by the Blupesca company, but they exit the system with the final product.

The wastes considered were disposed working gears, disposed socks and organic waste (damaged or dead mussels). Based on the data provided by the company, organic wastes are a significant part of the production, as they represent 30% of depurated mussels. They are a category 3 waste; therefore, it is required a specialized company for the disposal, which consist in an open burning procedure. Disposed tubular nets and working gears were both collected by municipal waste management company “Veritas s.p.a.”. Being a municipal waste, the company is not able to provide information on the amounts and the final disposal. It was assumed that 100% of PVC of working gears and 100% of PE of socks are disposed. Moreover, considering the Italian statistics on the recycling of plastic materials of municipal waste, it was decided to consider 70% of both PVC and PE recycled, while the remaining 30% disposed in an incinerator plant.

4.3.3 LIFE CYCLE IMPACT ASSESSMENT

Although the methods calculate more than 10 indicators, research in literature have shown that the main analysed categories in other LCA studies focusing on seafood productions are acidification, eutrophication, and global warming (*Pelletier et al., 2007)*. Therefore, in this phase these categories have been assessed. In addition to these categories, corresponding to AP, EP and GWP indicators, was chosen also the marine aquatic ecotoxicity considering the mussel farm position. In fact, only few studies include the toxicity impact (both on human and ecosystems), the land use or the water consumption indicators (*Aubin et al., 2009)*.

4.4 THE “SIMAPRO” SOFTWARE

While the first two phases of an LCA analysis do not necessary require the use of a specific software, the LCIA is generally carried out with purposely designed ones, such as SimaPro, GaBi and OpenLCA, which facilitate the modelling of the process/service analysed and include a range of methodologies for estimating the impact indicators. Herrmann et al. (2015) and Silva et al. (2017) showed that depending on the software used, conclusions can be widely different, so it is important to specify which tool is operating. In general, the SimaPro calculations lead to results that have a higher value of impact compared to the other calculations (*Silva et al., 2017*).

The model presented in this thesis was developed using SimaPro. The software provides a user interface for modelling the inventory, a database of processes, a database of different methodology to assess the impacts and a calculator that links the databases to the product system (*Pre-sustainability, 2012*). The software can be used to create sustainability reports, to elaborate environmental product declarations, to assess the carbon and water footprint, to analyse the eco-design of a product or to identify the indicators that describe the performance of a process (*simapro.*com). Although SimaPro was created as a tool to calculate environmental impacts, it has also been used to operate life cycle costing analysis, that is focused on the costs that a product generates during its life cycle (*Ciroth et al., 2009*).

Within the software, are also integrated the default or optional databases to identify the LCI processes and different methods to conduct the LCIA. In this thesis, the Ecoinvent database was applied and “ReCiPe (E)” and “CML IA baseline” methods were used to assess impacts.

4.4.1 “ECOINVENT” DATABASE

Inside the SimaPro software, different LCI database can be used to research processes, such as Agri-footprint, US Life Cycle Inventory database, AGRIBALYSE and others. Some of these are already present in the software package, while others must be downloaded afterwards (*simapro.com*). Among these, the one applied for this study is Ecoinvent database that is integrated by default in the SimaPro software.

This database was designed in the early 2000s by the Swiss Federal Offices. The official first version was released between 2003 and 2004 and it was compatible with some already-existing LCIA methods like Danish EDOP 1998, Dutch Eco-indicator 99 and CML 2001, Swedish EPS 2000, Swiss ecological scarcity 1997 and the Impact 2002+ (*Frischknecht et al., 2006*). Over the years, it was upgraded and implemented: in 2007 was released the second version and the third one in May 2013 (*Ecoinvent.org*). The implementations were required once the database started been used worldwide and not just in the European Union, for which it was created (*Wernet et al., 2016*). Currently, the latest version is Ecoinvent 3.8, which provides around 360 new databases and 700 updated datasets (*Ecoinvent.org*).

At present, the Ecoinvent database contains 18000 LCI datasets, which covers a wide range of sectors, such as agriculture, building and construction, chemicals, plastics, energy, wood, metals, transport, touristic accommodation, waste treatments and recycling. Whenever possible, processes are directly referred to a specific geographical area. Still, it is always represented the process with a global coverage, that means it is calculated as the average of the global production (*Ecoinvent.org*).

4.4.2 “CML IA – BASELINE” METHOD

Reviewing the literature, it was noticed that, even though ReCiPe is the mainly used worldwide for the LCIA analyses, CML was the predominant in the mussel’s industry. For this reason, the examination was conducted with both methods.

The CML is an impact assessment method, that was firstly developed by the University of Leiden (Netherlands) in 2001. There are two types of CML: baseline and non-baseline. In this thesis has been used the baseline one updated in 2016, that is the most applied (*Acero et al., 2016*). The CML analysis focuses on the impact generated by a series of 11 midpoints, also known as “impact categories” which are listed with their respective unit of measurement in Table 5.

These impacts are valid globally, except for the acidification and photo-oxidant formation which are strictly sensitive to the European context (*Acero et al., 2016*).

Table 5: impact categories of CML IA-baseline method

IMPACT CATEGORIES	UNIT
abiotic depletion	kg Sb eq
abiotic depletion (fossil fuels)	MJ
global warming (GWP100a)	kg CO2 eq
Ozone layer depletion (ODP)	kg CFC-11 eq
Human toxicity	kg 1,4-DB eq
Fresh water aquatic ecotoxicity	kg 1,4-DB eq
Marine aquatic 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

4.4.3 "RECIPE" METHOD

The "ReCiPe" method was first developed in 2008 by RIVM, Radbound University Nijmegen, Leiden University and PRé Sustainability (*pre-sustainability.com*). It was later upgraded in 2016 creating a more worldwide comprehensive version (*Huijbregts et al., 2016*) which makes it one of the most popular methods nowadays.

The aim of this method is to convert the LCI processes in an impact indicator value for each impact category. Indicators can either use the midpoint approach, applying 18 midpoints or the endpoint approach, applying 3 endpoints, both listed in Table 6.

Table 6: Midpoints and endpoints of ReCiPe method (Huijbregts et al., 2016)

MIDPOINTS	UNIT
Global Warming	Kg CO2 eq
Stratospheric Ozone Depletion	kg CFC11 eq
Ionizing radiation	kBq Co-60 eq
Ozone formation, human health	kg Nox eq

Fine particulate matter formation	kg SO2 eq
Ozone formation, terrestrial ecosystems	kg P eq
Terrestrial acidification	kg N eq
Freshwater eutrophication	kg 1,4-DCB
Marine eutrophication	kg 1,4-DCB
Terrestrial ecotoxicity	kg 1,4-DCB
Freshwater ecotoxicity	kg 1,4-DCB
Marine ecotoxicity	kg 1,4-DCB
Human carcinogenic toxicity	kg 1,4-DCB
Human non carcinogenic toxicity	kg 1,4-DCB
Land use	m2a crop eq
Mineral resources scarcity	kg Cu eq
Fossil resource scarcity	kg oil eq
Water consumption	m3

ENDPOINTS	UNIT
Human health	years
Ecosystems	Species/year
Resources	Dollars

Both endpoint and midpoint approaches can provide three different perspectives:

- The individualist approach focuses on the near future and the short-term impacts.
- The hierarchist perspective is usually the one used as default, and it is based on the most common policy principles.
- The egalitarian viewpoint provides a long-term vision, that is based on the precautionary principle, preferring more protective actions rather than avoidable future environmental problems.

In this thesis, it has been applied the egalitarian perspective, that is considered the most comprehensive and updated and it provides an overview on all environmental impacts.

5. RESULTS

In this chapter are shown the results obtained conducting the LCIA both with the ReCiPe (midpoint/endpoint) and the CML IA baseline methods. The results are presented at the normalization step on account of the fact that at this stage the impact values can be compared, although the units are not the same.

The complete table with the overall results and the weight of each process on the total outcome are presented in the Appendix C. While the reported graphs were created in Excel with the data obtained from the SimaPro software.

5.1 RESULTS USING CML IA-BASELINE

The results obtained conducting the analysis with the CML IA-baseline method are given in Table 7.

Table 7: Overall results of the analysed categories with the CML IA baseline method

CML IA-baseline		
Impact categories	**unit**	**total**
Global warming (GWP100a)	kg CO2 eq	0.41
Marine aquatic ecotoxicity (MAETP)	kg 1,4-DB eq	441
Acidification (AP)	kg SO2 eq	0.00228
Eutrophication (EP)	kg PO4--- eq	0.000663

As predictable the eutrophication potential is relatively low: less than 7 gr for each kg of mussels. This means that machineries, electricity consumed, and the materials used have a small potential impact to the surrounding marine algae ecosystems. However, this doesn’t apply to the marine aquatic ecotoxicity indicator, that shows a value higher than 400 kg 1,4-DB eq emitted in the seawater.

The acidification potential is a relative low value; therefore, mussels have a low capacity of causing a change in the pH of the surrounding seawater.

Lastly, the GWP100a calculated that for each kg of live weight depurated mussels there was an emission of 0.41 kg of GHGs.

Afterward the overall results were analysed, the single contributions of each process were investigated. Since the inventory collected 30 processes, for the contribution investigation these processes were grouped in 9 classes:

- The mussel farm including all the infrastructure used to grow the mussels, which are the wooden poles, steel ropes, a generator, and gas used for the generator.
- Socks were separated from the mussel farm group as they are consumables and not infrastructure. Moreover, in literature is common they have a relevant impact; therefore, it was considered important to keep them separately to the rest of the processes regarding the mussel farm.
- Boats are the only transport used by the company both in the re-socking and harvesting phases. Boats include boat hull, boat engine and gasoline.
- Electricity includes all the energy consumed in the land facility, that is mainly used for the operation of machineries.
- Machineries comprehend all depuration and packaging equipment.
- Pallets were used for the transportation outside the facility.
- Plastic nets, labels and clips are used for packaging procedures. Although they could be grouped in a single class representing the packaging phase, it was decided to consider these processes separately because they each have a significant impact on the total value.

In Fig. 11 are shown the resulting contribution of each of the classes created.

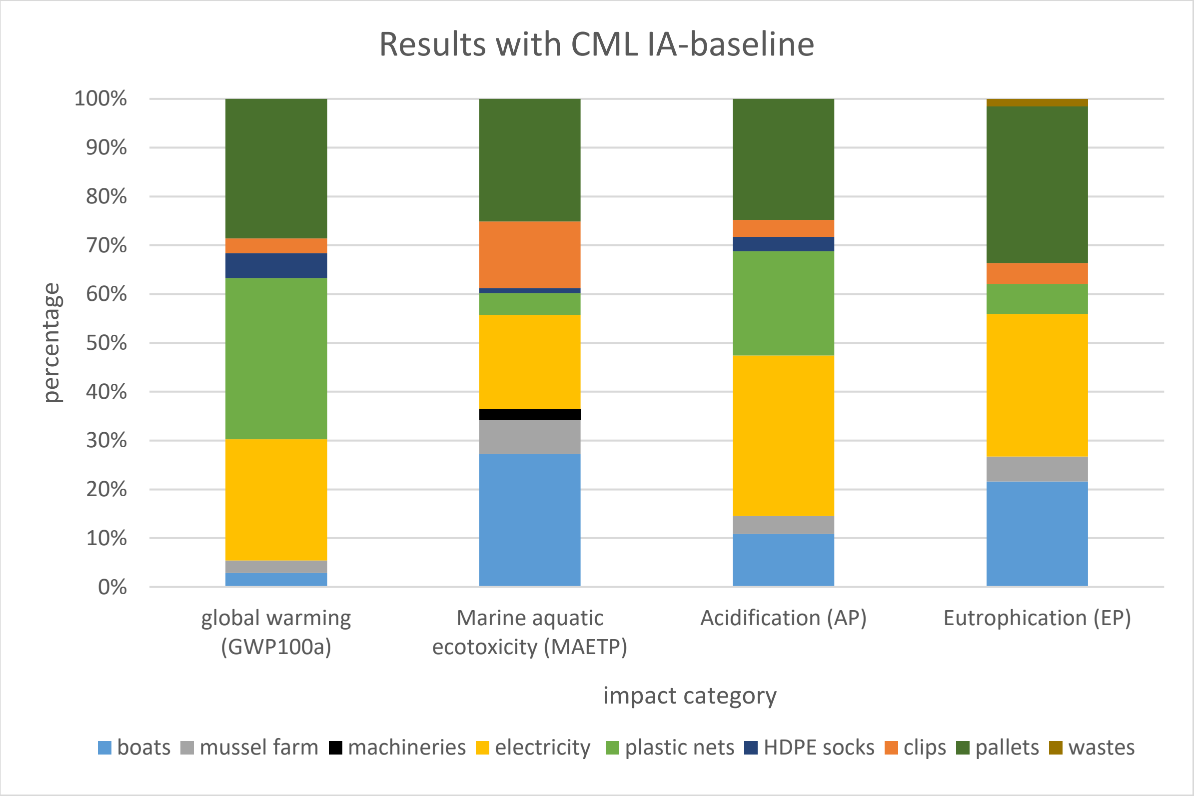


Figure 11: Results of the analysed impact categories with the CML IA baseline method

The results show that the impact generated by the infrastructure of the mussel farm is relatively small in all 4 categories (7% for MAETP, 5% for EP, around 3% for AP and GWP) compared to the impacts generated by the land facility, which comprehend both the depuration and the packaging procedures.

Electricity is relevant in all four categories, while machineries have only a small impact on the marine aquatic ecotoxicity. In this analysis the contribution of electricity is higher for AP and EP (32% and 28% respectively), while GWP100a and MAETP have a lower percentage of impact (24% and 19% respectively).

Another remarkable impact is presented by the packaging consumables (plastic nets, clips, labels, clips, and pallets), which are up to 64% in the global warming potential, around 50% for the acidification potential and 42% in the remaining categories. On the contrary for boats the company does not display such relevant percentages. It displays a significant contribution in MAETP, EP and AP indicators (respectively 27%, 21%, and 11%); however, in the GWP, boats account only for 3% of the total potential impact.

Finally, the impact of socks is only represented as a relevant percentage in the GWP (5%). Likewise, wastes are only represented in the EP with an irrelevant contribution.

5.2 RESULTS USING RECIPE (E)

The ReCiPe method present two types of analyses: midpoint or endpoint approaches. Both calculation of the two methods were carried out and interpreted comparing the outcomes with the results of the CML IA baseline method.

This method was not chosen as the principal for the study because of the lack of literature backgrounds; in fact, most of the mussel farming LCA analyses apply the CML IA baseline and only a few other bivalves' LCAs used this method. For this reason, the comparisons have been carried out with clams or oyster studies.

Midpoint

As presented in Table 8, the chosen impact categories of the "ReCiPe Midpoint (E)" methods are rather similar to the one calculated by the CML IA baseline, even though the unit of measurement differs for some indicators.

Table 8: Overall results of the analysed categories with the ReCiPe Midpoint method

ReCiPe Midpoints (E)		
Impact categories	**unit**	**total**
Global Warming	Kg CO2 eq	0.362
Terrestrial acidification	kg N eq	0.00198
Freshwater eutrophication	kg 1,4-DCB	0.000135
Marine eutrophication	kg 1,4-DCB	0.00000935
Marine ecotoxicity	kg 1,4-DCB	166

Indeed, the acidification is measured in kg of nitrogen eq. instead of kg of sulphur dioxide eq. The difference in the unit of measurement offers the opportunity to have additional information on the eutrophication process. The "ReCiPe" method shows the eutrophication measured in chemical compounds (dichlorobenzene) while the CML IA baseline method focuses on the amount of phosphate, which can be absorbed directly by the plants and algae. Because of the difference in the unit of measurement the only comparable categories are the global warming and the marine ecotoxicity. Although the order of magnitude was respected, both GWP and MAETP indicators calculated with the ReCiPe method show lower impact values than the ones obtained with the CML IA baseline method.

Moreover, unlike the CML IA baseline method, the "ReCiPe" divides the impacts generated by eutrophication on freshwaters and on seawater. Nevertheless, both indicators show low values.

In order to get a full comparison, the single contributions of the same classes of processes analysed before were investigated in Fig. 12.

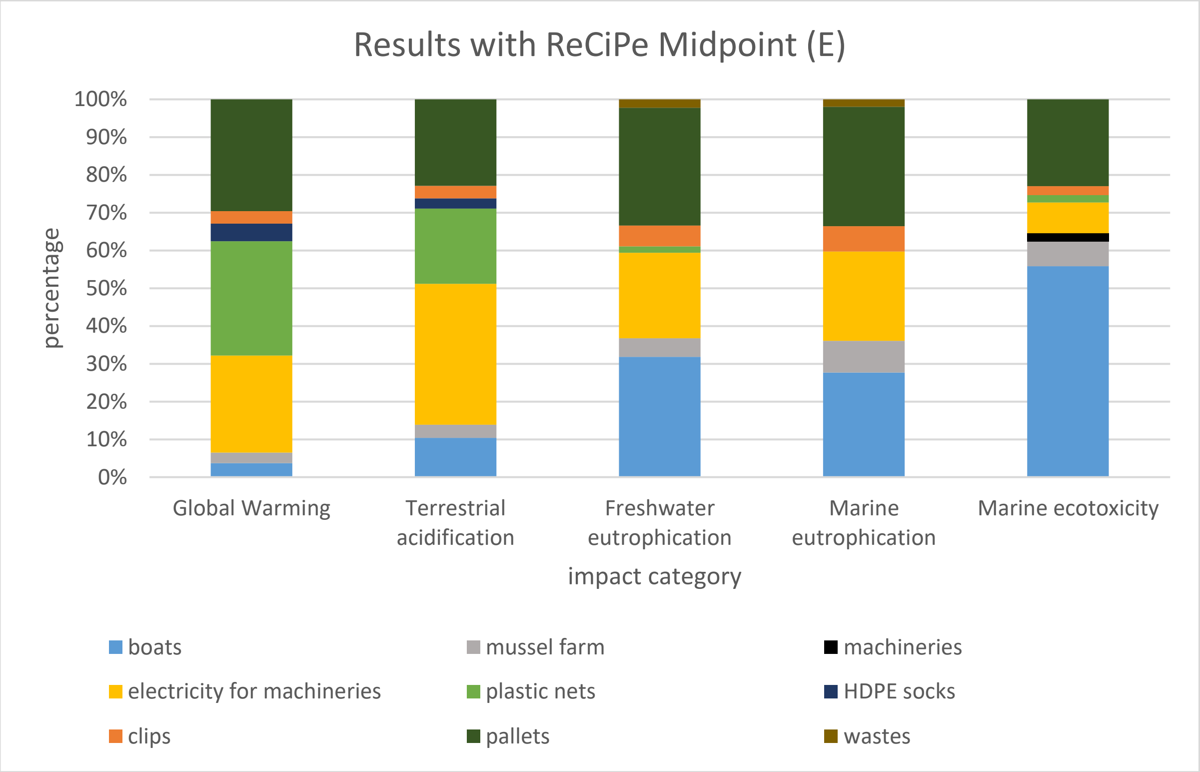


Figure 12: Results of the analysed impact categories with the ReCiPe Midpoint method

As far as GWP and AP concerns, the two methods show equal patterns. Also, marine and freshwater eutrophication potentials are quite alike, except for the plastic nets, which were not represented in the marine indicator. However, both indicators show relevant contributions of pallets, boats and electricity as was previously seen in the EP calculated with CML IA baseline.

The marine ecotoxicity is the only impact category that varies significantly from one method to another. Only pallets, machineries and mussel farm contributions are roughly kept the same. In the CML IA baseline analysis electricity had a higher value (around 20%) as in the ReCiPe analysis does not reach 10%. Likewise for the clips, which represent 13% of the total impact in the previous method, in the ReCiPe calculation it accounts for less than 3%.

In addition, the contribution of boats accounts for more than 50% compared to the 26% contribution in the CML IA baseline analysis.

Endpoint

Both CML IA baseline and ReCiPe midpoint approaches show the potential direct consequences of an input on the environment, while the endpoint approach shows the influence of the production on major context at the end of the cause-effect chain (*Dong et al., 2014*). In general, midpoints are more comprehensive and accurate, although usually for decision making are preferred endpoints which are considered to have a higher relevance. For this reason, usually experts recommend applying both methods (*Bare et al., 2000*).

The results of the endpoint approach obtained applying the ReCiPe method are shown in Table 9.

Table 9: Overall results of ReCiPe Endpoint method

ReCiPe Endpoints (E)		
Impact categories	**unit**	**total**
human health	DALY	0.0000433
ecosystems	species x year	3.32E-08
resources	USD	0.0738

Outcomes show that the biggest challenge for the company is the use of resources: for each kg of mussels 0.077 USD are spent to the overall resources consumed. While the impact on the natural ecosystems is insignificant and the one on human health is quite low.

For each of these categories, the contributions of each class of processes were analysed (Fig. 13).

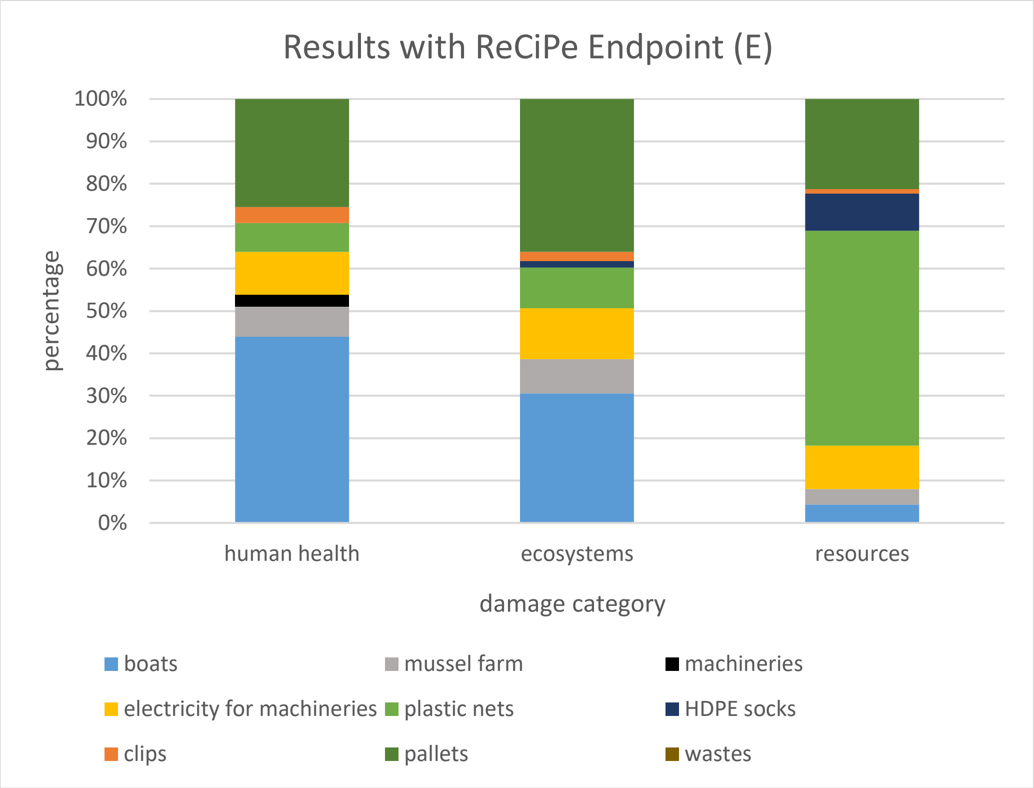


Figure 13: Results with ReCiPe endpoint method

As far as the human health concerns, the highest contribution comes from the boats (42%), while the remaining percentage is dominated by the packaging materials (up to 35%). While for the ecosystem's endpoint, the most damaging inputs are the packaging goods. Still the boats contribution is relevant (30%).

However, in the resource category boat are no longer relevant and the dominant percentage of the impact is due to the packaging goods, and in a small percentage of socks. In particular, inputs made of plastic materials are the one more impactful compared to aluminium clips and the wooden pallets.

Comparing these results with the ones from the midpoint approach, it can be seen that the electricity has a smaller impact in the damaging categories, while boats at the end of the cause-effect chain have a relevant influence on both human and ecosystems health. As shown in the midpoint approach the machineries have not a relevant impact in the analysed categories.

6. DISCUSSION

6.1 OVERALL ENVIRONMENTAL PERFORMANCE

The eutrophication potential shows a low value of impact; however, this value should be even lower if the ecosystem services provided by mussel farming would be taken into account: as filter feeders, mussels remove phytoplankton and organic particles, thus reducing the risk of eutrophication. Moreover, in ReCiPe method the eutrophication potential was divided; nevertheless, the sum of the two eutrophication indicators is similar to the impact generated by the clam's production (0.00016 kg 1-4-DCB), analysed with the same method, in a nearby geographical area (*Turolla et al., 2020*). This means in both methods the indicator shows a low potential impact on the surrounding environment.

Although the acidification potential is a relatively low value, the literature reviewed shows generally a smaller potential impact: Tamburini et al., (2020) display a value of an order of magnitude lower (0.00071 kg SO2 eq). This is also true for the marine aquatic ecotoxicity.

The GWP is considered low compared to other aquaculture LCA studies, such as trout from 0.76 kgCO2eq to 2.45 kgCO2eq (*Samuel-Fitwi et al., 2013*), sea beam around 1.87 kgCO2eq/kg, sea bass around 2.00 kgCO2eq/kg for sea bass (*Kallitsis et al., 2020*), salmon around 2.45 kgCO2eq/kg *(Ellingsen et al., 2006*), and Asian shrimps around 5.25 kgCO2eq/kg for (*Cao et al., 2011*). Whereas, if compared to other LCA studies on mussels, this value represents a slightly higher potential impact (*Tamburini et al., 2020 – Froesell, 2019*). However, this value does not consider the ability of mussels of absorbing CO_2 during their growth as they use it to develop their shells. Therefore, in order to get an accurate value of the CO_2 released, calculations should consider only the net value, which means the difference between quantities of the emitted GHGs and the absorbed ones (*Tamburini et al., 2022*). In general, several authors reviewed by Jansen and van den Bogaart in 2020 concluded that the overall carbon balance is still positive, because the sequestered CO_2 during the biocalcification is not enough to compensate the emitted amount.

6.2 RELEVANCE OF SINGLE CONTRIBUTIONS

In general, electricity, packaging materials and boats were the inputs generating the biggest contributions in the overall calculation of the potential impact in the analysed categories. Electricity was a primary data; therefore, no errors were generated in the impact analysis due to assumptions.

As other studies display the contribution of electricity is always significant (*Iribarren 2010, Lourguioui et al., 2017*) and its percentages in the four impact categories is similar to the ones displayed in the Lourguoiui et al. (*2017*). The electricity contribution, in fact, was expected to be high as the depuration process and the packaging procedures are relevant in the overall production. It was not possible to fully understand if this value could be considered high or low as, reviewing literature, LCA studies on mussels had only been carried out on longline farms, where the depuration process is not required (*Tamburini et al, 2020*). However, other studies (*Lourguioui et al., 2017*) demonstrated that also the longline farms consume a considerable amount of energy due to the usage of packaging equipment on boats. The potential impact of electricity is probably due to the fact that in Italy the electricity is mainly generated from fossil fuels. For this reason, suggesting using electricity from renewable resources could lead to a reduction of the impact. In order to implement the use of sustainable energies, practical and economic feasibility should be assessed.

The contribution of boats is significant; however, it not as relevant as in longlines farms studies. For example, in Tamburini et al. (2020) boats represent the main contribution: from 50% up to 85% of the total impact. In Tamburini study, the contribution of boat comprehends their on-board equipment. This value is probably due to the fact that in longlines farms mussels are usually cleaned and packed on boats and, when they reach the land, they already are a final product ready for distribution and consumption. This lead to the usage of bigger boats than the one used in the analysed company. Moreover, the Blupesca boats do not have to travel long distances as the farm is near the land facility, while longlines farms are located offshore. Assessing the environmental footprint with an endpoint approach, it was also possible to define that boats' impact is mainly due to their emissions, as they have a big contribution in the human health category. Whereas the impacts generated by materials or production process of boats and engines are diluted in their lifetime.

On the contrary, packaging materials have not such a high value in literature (*Tamburini et al., 2020*). Their largest impact is due to the consumption of resources, as shown in the homonymous damage category. Among the packaging materials the most impactful are made of petroleum-derived plastics, which is the most environmental impacting material compared to wood and aluminium, which are natural resources. The logic leads to assume that the impact of fossil resources is higher than the one of renewable ones. As far as the labels go, the Blupesca facility is already implementing the use of bioplastic to reduce its environmental footprint.

The same reasoning was applicable to the socks, which are made of HDPE and have only relevant impact in the resource endpoint. By replacing the petroleum-derived plastics with plastic derived from renewable raw materials and/or biodegradable materials for labels and plastic nets and with cotton for the socks, the environmental footprint could be reduced.

The rest of the inputs, such as machineries and mussel farm, had a smaller impact. The machinery low value was probably due the fact that it was only considered the material of which they are made and not the impact that their production process could generate. This could have led to an underestimation of their impact. However, it must be considered their long lifetime, which lead the value of the impact of a year to be smaller than the one generated in their whole lifetime. A similar logic could be applied to socks. Socks have an almost irrelevant impact in the analysis, while in literature they usually have a significant contribution to the overall impact (*Tamburini et al., 2020*). Due to lack of information, the amount of socks used was assumed making an educated guess researching information in this regard, but probably the assumption underestimated the actual quantity used.

Furthermore, socks cause other environmental problems which were not contemplated in this analysis. Socks often are inadvertently lost at sea and have became one of the most common waste found ashore along the Adriatic coasts. In waters near the mussel farms the presence of lost socks reaches 73 socks per square km. They pollute the water as they are a persistent waste with a degradation time of more than a century (*nuovaecologia.it, 2020*).

Lastly, the small impact of farming infrastructure could be compared to one of a longline system analysed by Tamburini et al. (2020). Likewise, wastes have an irrelevant impact; however, this value was not comparable with any LCAs on mussel farms, as in the aquaculture field, it is common to not include the waste treatment (*Parker et al, 2012*).

6.3 COMPARISON BETWEEN CML IA BASELINE AND RECIPE MIDPOINT METHODS

Applying both CML IA baseline and ReCiPe midpoint methods, it was possible to make a comparison between the results of the two. The outputs of the two methods were similar. However, the CML IA baseline overall values were slightly higher in each impact categories with the same unit of measurement (GWP and MAETP), therefore this method had applied a more precautionary analysis.

In addition, it has been noticed that the GWP, EP and AP indicators have a similar distribution of the contribution of each input in both methods, while the contributions of inputs in the MAETP indicator was significantly different from one method to another. Although, the MAETP overall score still has the same order of magnitude, ReCiPe method showed a greater contribution of boats, which is probably due to the higher sensibility of this method to potential impact caused by emissions.

Analysing only a subset of the impact categories calculated by both methods, it is not possible to provide a full comparison of the distribution of contributions in all impact categories. Moreover, the difference in units between indicators makes the comparison not doable.

6.4 MOST IMPACTING PHASE OF PRODUCTION

The impact assessment was carried out analysing the contribution of single inputs; however, it is possible to extract information about the different phases of the production. The supply chain is considered divided in three main stages:

1. the mussel farm includes farm infrastructure, socks, and boats used for both re-socking and harvesting procedures.
2. the depuration includes both the physical machineries and their electricity consumption. The electricity was also used for the packaging procedures; however, it was decided to include it in this phase as the majority is consumed for the depuration.
3. The packaging includes clips, pallets, labels and plastic nets used to pack the final product.

Among these phases the most affecting the environmental performance of the facility is the packaging, because of the large amount of plastic resources used to pack the mussels before shipment. While the other two phases have almost a similar contribution. However, in both mussel farm and depuration the infrastructures (wooden poles, ropes for mussel farm and machineries for depuration) have an irrelevant contribution compared to electricity and fuels consumed. This is probably due to the long lifetime of both machineries and farm, which reduce the impact.

Comparing the results of mussel farm phase between the thesis system and a longlines farm, it can be seen that both methods of mussel farming have a small contribution in the overall result (*Tamburini et al., 2020*). However, in a longlines farm the packaging is usually less impacting compared to the one measured in this thesis (*Tamburini et al., 2020*).

7. CONCLUSIONS

The thesis assessed the environmental footprint of a mussel farming production through a Life Cycle approach. In particular, it was investigated the production of a mussel farm located in a "B" zone, which, therefore, requires a depuration process of mussels before distribution and consumption. The aim of the study was to compare this production with an offshore farm, that do not need depuration and where usually the packaging is carried out on boats. The information provided by the Blupesca company have allowed a fairly accurate inventory, which led to an equally accurate analysis. The main limitations of the data collection were the assumption made for the mass and materials of machineries and the amount of socks used. Both have been approximated based on the literature and websites review and, comparing the results with other studies, it was possible to notice an underestimation of the socks contribution on the overall impact. While for the machineries it was not possible to define with certainty an underestimation as there are no studies on mussel farms requiring the depuration procedure.

Overall, the environmental footprint of the mussel supply chain is 0.41 kg of CO2 eq, similar to other LCA studies on mussels, while the fish aquaculture has a value of 1 kg CO2 eq or higher. This led to the conclusion, that in aquaculture field, mussel productions have a small environmental footprint, and it could be considered a green industry (*Tamburini et al., 2020, Runesson, 2020*). Waste to the overall impact assessment have an irrelevant contribution. Among the production phases the most impactful is the packaging, dominated by the materials used. Whereas the depuration is dominated by the electricity and the mussel farm phase by the contribution of boats. In order to reduce the most relevant contribution it was suggested to implement the use of renewable resources instead of fossil fuels and derivatives. Suggestion must undergo a further analysis to prove their feasibility in order to get both an environmental and economic advantage for the industry.

Comparing these results with longline mussel farms, it was possible to state that as far as the infrastructure goes longlines and fixed poles methods have similar contribution to the overall impact (*Lourguioui et al., 2017*), while there is a significant difference between the contribution of boats. In longlines, boats are usually bigger and equipped with packaging machinery, therefore their contribution has a 50% or higher value (*Tamburini et al., 2020*). Whereas in the analysed system, a relevant impact comes from the electricity consumed by machineries. In Lourguioui et al. (*2017*) a similar amounts of energy consumption were seen in an Algerian longlines farm. However, this input was not referred to energy consumed by depuration procedures but by both fuels and electricity for on board equipment. In conclusion, it was possible to state that the amount of electricity consumed by boats on longlines systems is roughly the same used for the depuration procedures.

Further studies should focus on the environmental footprint generated by the distribution and end of life phases in a cradle-to-grave approach. Although the impact of these stages is not expected to be as relevant as the one of the previous stages in the supply chain, their inclusion can offer a broad perspective. However, literature showed that up until now the LCAs conducted on the mussel farming sector have only explored a cradle-to-gate approach (*Vélez-Henao et al., 2021*).

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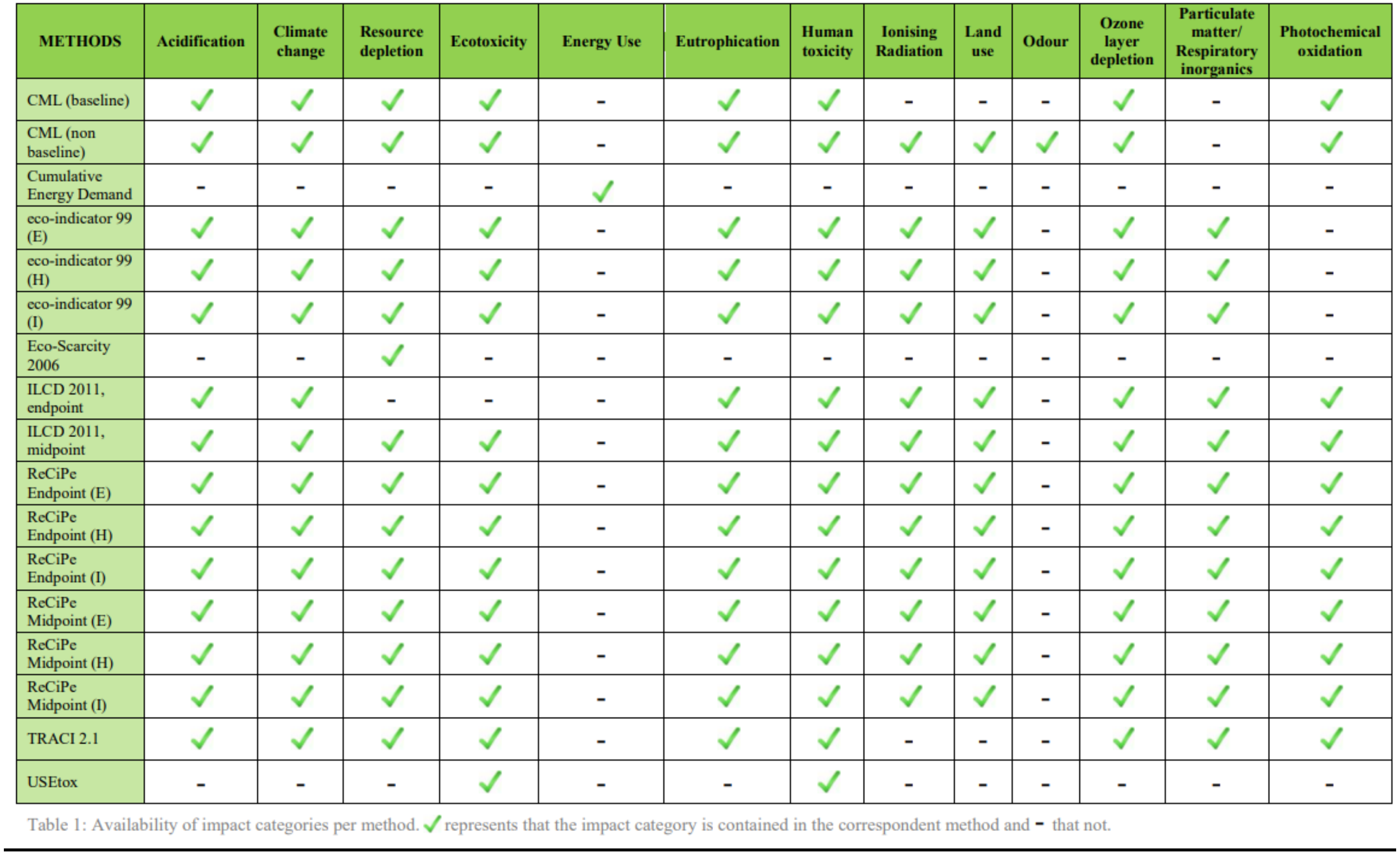
Appendix A

LCIA methods and respective impact categories *(Acero et al., 2016)*



METHODS	Acidification	Climate change	Resource depletion	Ecotoxicity	Energy Use	Eutrophication	Human toxicity	Ionising Radiation	Land use	Odour	Ozone layer depletion	Particulate matter/ Respiratory inorganics	Photochemical oxidation
CML (baseline)	✓	✓	✓	✓	-	✓	✓	-	-	-	✓	-	✓
CML (non baseline)	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	-	✓
Cumulative Energy Demand	-	-	-	-	✓	-	-	-	-	-	-	-	-
eco-indicator 99 (E)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	-
eco-indicator 99 (H)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	-
eco-indicator 99 (I)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	-
Eco-Scarcity 2006	-	-	✓	-	-	-	-	-	-	-	-	-	-
ILCD 2011, endpoint	✓	✓	-	-	-	✓	✓	✓	✓	-	✓	✓	✓
ILCD 2011, midpoint	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Endpoint (E)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Endpoint (H)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Endpoint (I)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Midpoint (E)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Midpoint (H)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Midpoint (I)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
TRACI 2.1	✓	✓	✓	✓	-	✓	✓	-	-	-	✓	✓	✓
USEtox	-	-	-	✓	-	-	✓	-	-	-	-	-	-

Table 1: Availability of impact categories per method. ✓ represents that the impact category is contained in the correspondent method and - that not.

Appendix B

A more comprehensive life cycle inventory

item	amount	unit	lifetime	value to 1 year	value to FU	unit	processes on simapro
INFRASTRUCTURE							
land occupation	1000	m2	20	50	0,00010101	m2	occupation, industrial area, build up
sea occupation	9106	m2	20	455,3	0,004516865	m2	occupation, sea and ocean
boat hull	1000	kg	50	20	0,000198413	kg	glass fibre [RER]|production, cut-off U
ropes - steel	2267,67	kg	20	113,3835	0,001124836	kg	steel, chromium steel 18/8 [RER]| steel production, elettric, chromium steel 18/8, cut-off U
wooden poles	217086,57	kg	20	10854,3285	0,000224337	kg	Sawnwood, hardwood, raw {RoW}| sawing, hardwood | Cut-off, U
bins (tanks)	1533	kg	25	61,32	0,000123879	kg	Polyethylene, low density, granulate [RER]| production| cut-off, U
MACHINERY							
on boats							
boat engine	1	quantity	7	0,142857143	1,41723E-06	unit	Marine electric motor {GLO}| marine electric motor construction | Cut-off, U
generator	1	quantity	20	0,05	4,96032E-07	unit	heat and power co-generation unit, 50 kW electrical, components for electricity only [RER]| construction| cut-off, U
water captation							
submersible pump	1	quantity	12	0,083333333	8,2672E-07	unit	Pump, 50W [RoW]| production| Cut-off, U
pipelines for water transportation	3,5	kg	50	0,07	1,41414E-07	kg	Polyvinylchloride, emulsion polymerised [RoW]| polyvinylchloride production, emulsion polymerisation| Cut-off, U
depuration systems							
Skimmer	5	kg	5	1	2,62626E-05	kg	glass fibre [RER]|production, cut-off U
UV lamps	20	quantity	5	4	8,08081E-06	unit	Ultraviolet lamp {GLO}| ultraviolet lamp production, for water desinfection | Cut-off, U
Sand bio filters	1500	kg	5	300	0,000606061	kg	Inert filler [GLO]| sand to generic market for| Cut-off, U
Chiller	2	quantity	25	0,08	1,61616E-07	unit	Refrigeration machine, R134a as refrigerant [GLO]|production| Cut-off, U
weighting and packaging							
water tanks	680	kg	25	27,2	5,49495E-05	kg	Polyethylene, linear low density, granulate [RER]| production| Cut-off, U
brushing machine (spazzolatrice)	600	kg	25	24	4,84848E-05	kg	steel, chromium steel 18/8 [RER]| steel production, elettric, chromium steel 18/8, cut-off U
hopper with conveyor belt and automatic weighting	1500	kg	25	60	0,000595238	kg	steel, chromium steel 18/8 [RER]| steel production, elettric, chromium steel 18/8, cut-off U
debysser (sbissatrice)	150	kg	25	6	5,95238E-05	kg	steel, chromium steel 18/8 [RER]| steel production, elettric, chromium steel 18/8, cut-off U
conveyor belt (nastro di selezione)	2,6	m	25	0,104	1,03175E-06	m	Conveyor belt [RER]| production| Cut-off, U
manual clipper	80	kg	25	3,2	3,1746E-05	kg	steel, chromium steel 18/8 [RER]| steel production, elettric, chromium steel 18/8, cut-off U
platform scale	75	kg	25	3	6,06061E-06	kg	steel, chromium steel 18/8 [RER]| steel production, elettric, chromium steel 18/8, cut-off U
classical scale	10	kg	25	0,4	8,08081E-07	kg	steel, chromium steel 18/8 [RER]| steel production, elettric, chromium steel 18/8, cut-off U
CONSUMABLES							
socks	109	kg	1	109	0,01	kg	Polyethylene, high density, granulate [RER]| production| Cut-off, U
clips	150	kg	1	150	0,001488095	kg	Polyethylene, high density, granulate [RER]| production| Cut-off, U
labels	19,764	kg	1	19,764	0,000196071	kg	aluminium, primary, ingot [IAI Area, EU27 & EFTA]| production| Cut-off, U
pallets	1600	quantity	1	1600	0,015873016	unit	Polyethylene, high density, granulate [RER]| production| Cut-off, U
plastic nets	6000	kg	1	6000	0,05952381	kg	EUR-flat pallet [RER]| production| Cut-off, U
working gears	10,2	kg	1	10,2	0,00010119	kg	Polyethylene, low density, granulate [RER]| production| Cut-off, U
seawater	1.095.000	L	1	1.095.000	0,002212121	L	Polyvinylchloride, suspension polymerised [RER]| polyvinylchloride production, suspension polymerisation | Cut-off, U
							Water, selt, ocean
ENERGY							
Electricity for machinery	110000	kWh	1	110000	0,222222222	kWh	
Gasoline boat	525	L	1	525	0,003965729	L	Electricity, medium voltage {IT}| electricity voltage transformation from high to medium voltage | Cut-off, U
Gas for generator	532,7245053	m3	1	532,7245053	0,003472222	m3	Petrol, unleaded {Europe without Switzerland}| petroleum refinery operation | Cut-off, U"
motor oil	4,165	kg	1	4,165	4,13194E-05	kg	Natural gas, from medium pressure network (0.1-1 bar), at service station {RoW}| processing | Cut-off, U
OUTPUT							
organic waste	3270	kg	1	3270	0,032440476	kg	animal matter

Waste management

item	waste	avoided waste	output	energy	description
working gears	PVC	7,08333E-05	3,03571E-05	1	In Italy is recycled 70% of the plastic waste
socks	PE	0,007	0,003	1	In Italy is recycled 70% of the plastic waste
organic wastes	other	0	0,032440476	1	Open burning

Appendix C

All results from the LCIA of ReCiPe Midpoint, ReCiPe Endpoint and CML IA baseline, comprehending all the impact categories. The single contributions of the processes are in percentage of the total.

ReCiPe (E) Midpoints

Impact categories	unit	total	land occupat	sea occupat	boat h	ropes	wooden pc	bins	boat engi	generat	pump	pipeline	Skimmer	UV lamps	Sand bio filt	Chiller	water tanks	brushing mac	automatic weighting	debyss	conveyor belts	manual clipper	platform scale	classical sc	socks	clips	labels	pallets	plastic nets	working ge	seawat	Electricity for machi	Gasoline b	Gas for genera	motor c	wastes
al Warming	Kg CO2 eq	**0,362**				1,11	1,55		2,86																4,54	3,16		28,5	29,1			24,8	0,73			
Stratospheric Ozone Depletion	kg CFC11 eq	**0,000000247**				0,875	2,6		4,56																	2,51		34,6				48,5	1,73			1,03
zing radiation	kBq Co-60 e	**0,048**				1,03	4,99		2,87																	7,88		29				45	2,77			3,95
Ozone formation, human health	kg Nox eq	**0,00117**				1,09	3,15		3,57																3,44	2,24		43,3	23,7			15,8	0,711			
Fine particulate matter formation	kg SO2 eq	**0,000746**				2,45	1,16		9,58	1,3									1,3						2,29	3,16		36	16,4			22,9	1			
Ozone formation, terrestrial ecosystems	kg P eq	**0,00126**				1,03	3,42		3,4																3,59	2,11		43,2	24,6			14,9	0,7			
estrial acidification	kg N eq	**0,00198**				1,05	1,11		9,02	1,25															2,67	3,22		22,3	19,4			36,3	1,11			
hwater eutrophication	kg 1,4-DCB	**0,000135**				1,33			30,5	3,44																5,29		29,9	1,6			21,7				2,11
ine eutrophication	kg 1,4-DCB	**0,00000935**				1,23	3,88		26,5	2,89																6,37		30,2				22,6				1,89
estrial ecotoxicity	kg 1,4-DCB	**2,07**				5,53	1,57		51,9	4,96									2,93									25				4,52				
hwater ecotoxicity	kg 1,4-DCB	**0,0167**				2,04			43,5	4,38						1,69			1,08		1					8,01		20,9	1,98			11,9				2
ine ecotoxicity	kg 1,4-DCB	**166**				1			54,1	5,46						1					1,02					2,32		22,3	1,85			7,91				
Human carcinogenic toxicity	kg 1,4-DCB	**2,15**				10,6			10,7	1,58									5,61		2,97				1,49	13		29,9	12,4			7,69				
Human non carcinogenic toxicity	kg 1,4-DCB	**137**				0,837			55,5	5,6											1,01					1,54		22,3	1,77			7,74				
d use	m2a crop ec	**0,673**					17,3																					82,1								
eral resources scarcity	kg Cu eq	**0,00287**				18,2			30,5	2,48									9,62		1,91					8,73		20,1				2,89				
il resource scarcity	kg oil eq	**0,2**				0,534			1,37																7,81	1,21		22,2	45,9			13,7	2,54	2,14		
er consumption	m3	**0,00495**					1,39																		2,74	9,23		22,1	21,2			36,8				1

ReCiPe (E) Endpoints

Impact categories	unit	total	land occupat	sea occupat	boat h	ropes - st	wooden pc	bins (tanl	boat engi	generat	submersi	pipeline	Skimmer	UV lamps	Sand bio filt	Chiller	water tanks	brushing mac	automatic weighting	debyss	conveyor belts	manual clipper	platform scale	classical sc	socks	clips	labels	pallets	plastic nets	working ge	seawat	Electricity for machi	Gasoline b	Gas for genera	motor c	wastes
an health	DALY	**0,0000433**				2,49			42,1	4,38									1,32		1,26					3,62		24,4	6,55			9,68				
ystems	species x yea	**3,32E-08**				0,857	3,9		29,6	3,1															1,43	2,15		34,9	9,31			11,6				
urces	USD	**0,0738**				0,5	1,09		1,18																8,65	1		21	50,1			10,1	3,09	2,03		

. IA-baseline

Impact categories	unit	total	land occupat	sea occupat	boat h	ropes - st	wooden pc	bins (tanl	boat engi	generat	submersi	pipeline	Skimmer	UV lamps	Sand bio filt	Chiller	water tanks	brushing mac	automatic weighting	debyss	conveyor belts	manual clipper	platform scale	classical sc	socks	clips	labels	pallets	plastic nets	working ge	seawat	Electricity for machi	Gasoline b	Gas for genera	motor c	wastes
tic depletion	kg Sb eq	**0,00000185**				7,5	1		49,5	4,87						3,07			3,97							3,89		20,6				2,32				
abiotic depletion (fossil fuels)	MJ	**8,5**							1,37																7,8	1,21		22,3	45,8			13,6	2,59	2,08		
al warming (GWP100a)	kg CO2 eq	**0,41**				1,05	1,44		2,72																4,88	2,88		27,3	31,6			23,7				
Ozone layer depletion (ODP)	kg CFC-11 ec	**0,000000031**					3,67		2,05							2,36										3,13		36,6				36,4	8,94	3,34		
an toxicity	kg 1,4-DB ec	**0,461**				18,5			24,4	1,67									9,76							2,3		31,7	1,49			4,68				
h water aquatic ecotox	kg 1,4-DB ec	**0,176**				9,36			25,5	2,3						1,12			4,95							11,1		24,4	2,2			13,7				
ine aquatic ecotoxicity	kg 1,4-DB ec	**441**				4,1			26,2	2,59									2,16						1	13,1		24,2	4,27			18,6				
estrial ecotoxicity	kg 1,4-DB ec	**0,00124**				12,3	6,88		11,9	1,46									6,52		1,86					2,96		31,1				18,2				2,04
tochemical oxidation	kg C2H4 eq	**0,000146**					7,92		6,6																4,27	4,7		40,1	17,1			13,5	1,03			
ification	kg SO2 eq	**0,00228**				1,12	1,17		9,38	1,3															2,87	3,41		24,1	20,8			32	1,17			
ophication	kg PO4--- eq	**0,000663**				1,26	1,28		20,8	2,4																4,11		30,9	5,93			28,1				1,5