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Evaluation of Environmental Hotspots and improvements for sustainable mussel production: An LCA approach on the case study of La Spezia (Italy)

Letizia Caroscio [a,*], Cristian Chiavetta [b], Alessandra Bonoli [a]

[a] Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Italy
[b] ENEA - Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Italy

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ABSTRACT

This study presents a Life Cycle Assessment (LCA) of mussel farming in the Gulf of La Spezia (Liguria, Italy), a site of particular interest due to its proximity to the Cinque Terre National Park, the presence of a major industrial port, and the coexistence with traditional aquaculture practices. Innovatively, this study combines LCA with alternative scenarios analysis to explore circular economy strategies in mussel farming, providing practical solutions to reduce environmental impact and valorize by-products.

The results highlight the importance of reducing imports, limiting the use of plastic materials, and optimizing waste management practices. In particular, the farming phase, mainly driven by the import of mussels from abroad, accounts for more than 90 % of the total impacts in 10 out of 11 categories analyzed. Scenario analysis shows that reducing imports by 50 % (Scenario C) decreases impacts by about 42–48 %, while their complete elimination (Scenario D) leads to drastic reductions, exceeding 85 % in all categories and reaching up to 97 % for Global Warming.

The goal is to advance toward a sustainable and circular blue economy model that supports environmental protection, promotes responsible food, and contributes to the development of the local economy while also addressing new production scenarios.

1. Introduction

Food demand is expected to increase significantly in the coming years, and food production is one of the main factors impacting climate change through land use, water consumption, and CO_2 emissions (Crippa et al., 2021; Foley et al., 2011; Garnett, 2011). Addressing the challenge of feeding a global population that has surpassed 8 billion people raises complex and widely debated issues (Cirera and Masset, 2010; Food and agriculture organization, 2009; Godfray et al., 2010; Zurek et al., 2018).

The supply of fish resources, exacerbated by overfishing, illegal activities, and ecosystem destruction, has reduced fish populations, increasingly pushing towards an expansion of aquaculture (Battista et al., 2018; Food and agriculture organization, 2001; Jackson et al., 2001). From 1990 to 2020, annual aquaculture production saw a growth of 609 %, with an average annual growth rate of 6.7 % (Food and agriculture organization, 2001). Although aquaculture offers significant benefits such as increased access to animal proteins and the creation of millions of jobs, especially in developing countries, it is also associated with significant environmental impacts (Martinez-Porchas and Martinez-Cordova, 2012). The sustainability of aquaculture greatly depends on the species farmed, the intensity of production, and the location of the facilities (Hammer et al., 2022; Soliño and Figueras, 2025).

In this context, mussels farming emerges as a form of aquaculture with a lower environmental impact, making it one of the most sustainable sources of animal protein (Yaghubi et al., 2021). However, the environmental impact of these practices remains higher compared to major sources of plant proteins, which are often recognized as a solution for a balanced diet that protects not only human health but also animal health and the planet (Ferrari et al., 2022; Jacob et al., 2016; Willett et al., 2019).

Mussels feed by filtering phytoplankton, algae, and other organic particles naturally present in the water, thereby eliminating the need to add feed or additives such as vitamins or antibiotics (Wijsman et al., 2019). This results in lower impacts on both consumption and ecosystems unlike other intensive aquaculture practices. Moreover, as sessile organisms, mussels can be grown within tubular nets that minimize the occupation of marine space (Suplicy, 2020a).

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* Corresponding author. Via Umberto Terracini 28, 40131, Bologna, BO, Italy.
E-mail address: letizia.caroscio2@unibo.it (L. Caroscio).

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Despite the inherent sustainable aspects, some processes in mussel farming can be made more efficient along the entire production cycle, from local sourcing of the product to energy consumption and the reuse of processing waste. This research aims to further explore the issue through a Life Cycle Assessment (LCA) of mussel farming. The goal is to identify and optimize the environmental hotspots of the production process, to further reduce impacts and promote production practices that are consistent with an even broader sustainability approach.

Mussel farms represent a fundamental component of the blue circular economy, a strategy aimed at sustainably optimizing the use of marine resources (Borriello et al., 2023). This economy not only considers sustainable food production from the sea but also includes the management and recycling of waste, minimizing environmental impact, and improving the health of marine ecosystems.

Mussel farming has grown significantly globally in recent years, being recognized not only for its economic value but also for the environmental benefits it could offer, as well as for the simplicity of the farming type which is well-suited to be introduced as a potential activity to increase in growing countries (Alonso et al., 2021; van der Schatte Olivier et al., 2020; Vaughn, 2018a).

The Global Mussels Market reached US$ 4.4 billion in 2022 and is expected to reach US$ 6.3 million by 2030 (European Commission, 2019). China is the largest producer, followed by other significant countries such as Chile and Spain. In 2021, mussel production in the European Union accounted for more than a third of the total aquaculture output, reaching 425,242 tonnes and a value of 479 million euros, the highest in a decade. This marked a 5 % increase in volume and a 22 % increase in value compared to 2020. Despite a previous downward trend until 2020, 2021 saw the first increase since 2017, particularly due to production boosts in Italy and France (European Commission: Directorate-General for Maritime Affairs and Fisheries, 2022). In 2022, Italy produced about 52,546.8 tons of mussels, with 4 % of the production coming from the Liguria region. Eurostat data indicates that Italian mussel production has fluctuated over the past decade, with a slight downward trend, decreasing from over 79,000 tons in 2011 to less than 51,000 tons in 2020 (European market observatory for fisheries and aquaculture products, 2022). One of the causes of the production decline is related to the presence of species such as blue crabs or sea bream that damage the harvest.

This research focuses on the Liguria region, particularly the cities of La Spezia, Lerici, and Portovenere, where, for the first time, a dedicated LCA analysis is conducted on mussel farming, an activity that serves as an economic and cultural pillar for the local community. The Gulf of La Spezia was selected as a case study not only for its long-standing tradition of mussel farming, but also for its distinctive and complex environmental setting. The area combines high ecological and naturalistic value, being adjacent to the Cinque Terre National Park, at the heart of the Pelagos Sanctuary for the protection of marine mammals in the Mediterranean, and other protected marine areas, with the presence of major industrial and military infrastructures, including a commercial port and a naval base. This coexistence of natural value and anthropogenic pressure makes the site particularly relevant for evaluating the environmental performance of aquaculture systems in sensitive coastal zones. Furthermore, the relatively limited scale of local production, compared to other Italian regions, represents an advantage in terms of manageability and the potential to act as a pilot site for testing innovative practices and transitioning toward more sustainable mussel aquaculture. Finally, since Italy is a peninsula with aquaculture distributed across multiple seas, this study also provides the first Life Cycle Assessment focused on the Tyrrhenian coast, thereby complementing the existing literature mainly concentrated on the Adriatic and enabling broader geographical comparisons.

While many studies have analyzed the environmental impacts of aquaculture, few have focused on mussel farming within the framework of a circular blue economy. This study introduces an innovative contribution by not only assessing the baseline performance through LCA, but also by configuring and testing alternative scenarios. Such scenario analysis provides insights into potential improvement measures, such as reducing imports, adopting renewable energy, or valorizing by-products, that can guide strategies for enhancing the sustainability and efficiency of mussel production systems.

The objective of this study is to position mussel farming within a model of circular economy and sustainability through an analysis of environmental impacts and alternative scenarios. This approach aims to improve current practices, aligning them with contemporary environmental needs, and to support sustainable and responsible diets.

2. Material and methods

2.1. Study area and case analysis

The province of La Spezia is located in the eastern part of Liguria, adjacent to the Tuscany region, and is one of the smallest provinces in Italy. The Gulf of La Spezia, the subject of this study, is a significant maritime area in the northwest of the Tyrrhenian Sea(Fig. 1). The gulf is about 4.5 km long and 3.5 km wide, and its importance stems from the presence of strategic commercial and military infrastructure. The gulf hosts an important arsenal of the Italian Navy and a commercial port specialized in container management and cruise ship traffic. A 2210-m-long breakwater crosses the gulf, connecting Punta Santa Maria to Punta Santa Teresa, regulating maritime access through two channels of 400 and 200 m (Liguria Region, 2018).

The presence of the breakwater protects the gulf from storm surges, creating optimal conditions for mussel growth, supported by favorable environmental conditions and the low coastline. The mussel farming installations are along the breakwater's inner side and on the eastern and western outer sides between Portovenere and Palmaria Island (Balbi et al., 2017). These areas are managed by the Cooperativa Mitilicoltori Spezzini, responsible for the cultivation, harvesting, and distribution of La Spezia mussels. Founded in 1983, the cooperative has 87 members and includes all mussel farmers operating in the gulf, representing a key entity in the local and regional economy.

Italian mussel production is distributed across 12 of the 20 regions, with a strong concentration along the northern Adriatic coast. In contrast, installations in the Tyrrhenian area are fewer and more localized. Liguria accounts for about 4 % of national production, yet mussel farming in the Gulf of La Spezia plays a significant cultural and economic role for the region. The cooperative model, coupled with the distinctive environmental and infrastructural context of the gulf, makes this site particularly relevant for assessing sustainability challenges and opportunities. To the best of our knowledge, this is the first study applying LCA to mussel farming on the Tyrrhenian coast, complementing the existing literature that has so far mainly addressed Adriatic production systems.

2.2. Methodology

This study analyzes mussel production in La Spezia through an integrated circular economy approach. It evaluates the potential and environmental issues, identifying possible flows for recycling chains, and examines current regulations to explore the possibility of reusing waste materials. For these assessments, the LCA method is adopted according to standards (EN_ISO_14040, 2006; EN_ISO_14044, 2021). The overall methodology is structured into four main phases: Goal and Scope Definition, Life Cycle Inventory analysis, Impact Assessment, and Results Interpretation (Joint Research Centre, 2010). This approach aims to provide a detailed analysis that supports the optimization of processes and the implementation of sustainability and recycling strategies in mussel farming in La Spezia.

2.2.1. Goal and Scope Definition

The primary objective of this study is to identify and optimize the

Fig. 1. Mussel Farming in the Gulf of La Spezia (Source: authors).

environmental hotspots associated with mussel farming practices, aiming to mitigate them to reduce environmental impact and promote more sustainable production methods in the Liguria region, particularly in the cities of La Spezia, Lerici, and Portovenere. The functional unit is defined as the total annual mussel production by the 86 members of the Cooperativa Mitilicoltori Spezzini in 2022, amounting to 2700 tons, to which all input and output flows of the system refer. Since the mussel farming sector is characterized by interannual variability, determined both by biological factors, such as predation by other marine species or variations in mortality rates due to environmental conditions, and by economic and market factors, such as fluctuations in demand for imported products, it was deemed appropriate to adopt the actual production for the year 2022 as the functional unit.

This choice was considered the most appropriate for the present study, since all the primary data collected refer to this specific year, ensuring consistency and representativeness with respect to the actual scenario analyzed. This choice limits the study, making it very accurate for the reference year but not extendable to other contexts. However, in section 3.3, the results have been reworked to facilitate a broader and more generalizable reading that also allows for comparison with the results of other studies.

The assessment was conducted using an attributional LCA with a cut-off approach, employing SimaPro software version 8.5. To meet the specific objectives of the study and considering the geographical area examined, the modeling was carried out using the CML-IA baseline methodology V3.07 (Guinée, 2001). This enabled a comprehensive and in-depth evaluation of the environmental effects of mussel farming and the production hotspots. Eleven environmental impact categories were analyzed: Abiotic depletion, Abiotic depletion (Fossil Fuels), Global Warming Potential (100 years) Ozone Layer Depletion, Human Toxicity, Freshwater Aquatic Ecotoxicity, Marine Aquatic Ecotoxicity, Terrestrial Ecotoxicity, Photochemical Oxidation, Acidification, and Eutrophication.

2.2.2. *System boundaries*

This study, adopting a cradle-to-gate boundary, focuses on mussel production, considering the processes of seeding and monitoring, harvesting, farming, processing, purification and packaging of mussels. To provide a comprehensive view of the system, the transportation of production and processing waste is also considered. The distribution, sale, use, and end-of-life phases of the product are excluded from the analysis. Additionally, the study does not include the flows related to the construction of the mussel farming facility and the use of materials for building mussel farming structures.

Waste that can end up in the sea during farming, such as nets or shells, was not modeled due to the lack of accurate data and estimates. In aquaculture impact assessments, the quantification of plastic dispersion attributable to individual companies, or in this case to a mussel farmers' cooperative, remains challenging: even when debris is retrieved, it is not always possible to reliably trace it back to a specific geographical area, to the year of dispersion, to a particular aquaculture activity, or to determine what share of overall dispersion it represents (Skirtun, 2022). For this reason, this issue could not be explicitly integrated into the present modeling. It should nevertheless be noted that growing awareness among operators is contributing to reducing gear loss, although dispersions caused by storms, adverse sea conditions, or interactions with marine species remain difficult to avoid.

The system boundaries are delineated in the flow chart (Fig. 2) as follows.

- Seeding and Monitoring: includes the collection of wild mussel seeds through local capture, the use of boats to reach the nurseries for seeding, and the maintenance of the facilities.
- Farming: encompasses the use of boats to access the nurseries and the purchase of mussels imported from Galicia (Spain), transported under refrigerated conditions. It also considers the use of work materials such as latex and nitrile rubber gloves, their packaging, and

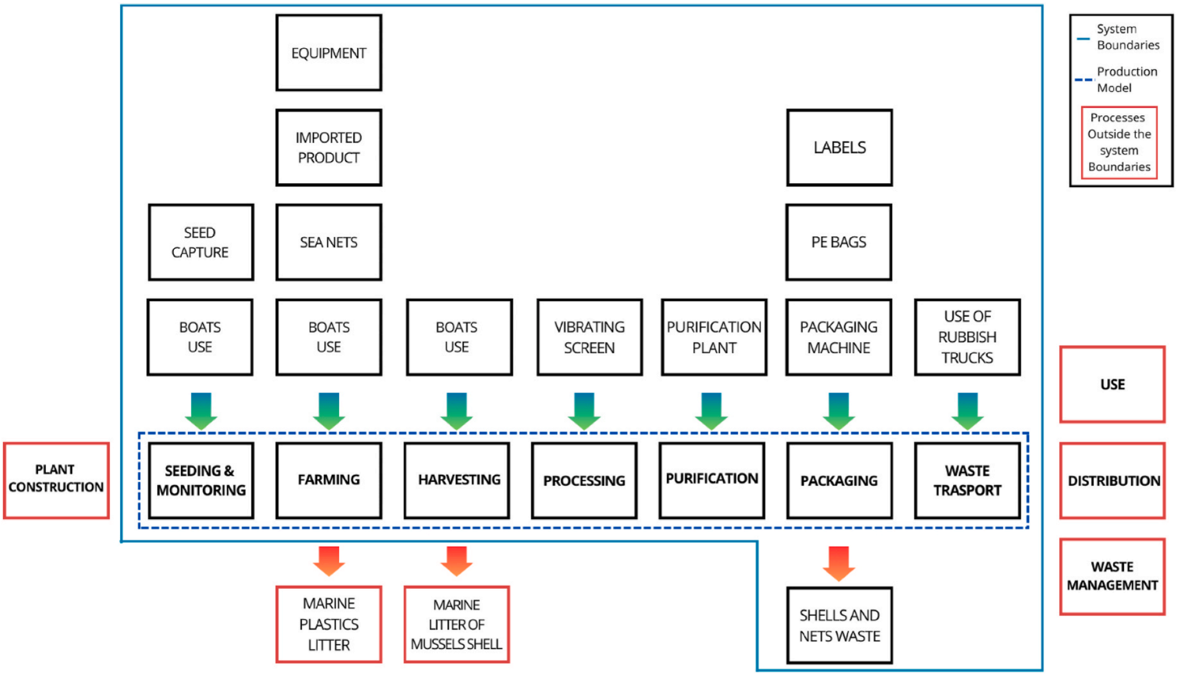

Fig. 2. Flow chart schematizing the system boundaries of Life Cycle Assessment (LCA). The diagram highlights within the continuous green line all phases included in the study.

transport from the supplier. Additionally, it includes the nets used for mussel cultivation, their packaging, and transport from the supplier.

- Harvesting: entails the use of boats to extract mature mussels from the nurseries and manage waste, including broken or discarded nets.
- Processing: includes the energy consumption required for cleaning and sorting mussels through vibrating sieves.
- Purification Plant: the facilities, located in category B waters (Regulation (EC) No 854/2004, 2004), require purification treatment. Mussels are treated in bins with sterilized water for 24 h, using an ozone sterilization process that does not alter the product's organoleptic properties. The energy consumption related to purification and maintaining a constant temperature of 22 °C is considered.
- Packaging: takes into account the use of polyethylene plastic nets for packaging, labels for identifying and dating the fresh product. It also includes the transport of these nets and labels from the supplier and their packaging. The energy consumption of automatic packaging machines and storage in refrigerated cells is also included.
- Waste transport: includes the management and transport of waste from the production process on land. Shell waste is routed to an animal by-product treatment plant. Plastic waste follows a different route and is managed as non-hazardous special waste at another facility. In contrast, waste generated outside the facility related to the distribution or use phase is not evaluated because it is outside the system boundaries.

2.2.2.1. Life Cycle Inventory. To conduct the life cycle analysis, primary data were collected through a series of direct interviews with representatives of the "Cooperativa Mitilicoltori Spezzini," on-site observations, and in-depth analyses of company databases. These data include details on the cultivation techniques employed, resource usage, energy consumption, waste management strategies, and processing practices adopted by the cooperative. Specifically, the primary data collected comprise the electrical energy consumption of the stabilization plant, measured through energy bills during 2022, the quantity of plastic materials used (polyethylene PE, polypropylene PP, high-density polyethylene HDPE) related to tubular socks, plastic nets, labels, and gloves, recorded through purchase and billing data. Additionally, the transport of these materials from the manufacturer to the cooperative and the use of packaging for transport and packaging were documented. Primary data also evaluated the volumes of waste generated by the production process in 2022 and their transport to treatment plants. Data regarding the product imported from Galicia and purchases made in 2022 were also collected as primary data through invoices. The consumption and hours of use of machinery and information on the daily operations of the boats were obtained through interviews with mussel farmers.

Overall, all the data used in the study were collected as primary data, with only two exceptions incorporated into the LCA model through the Ecoinvent database version 3.8 (Frischknecht et al., 2005): (i) the transformation of plastic nets from granulated material, and (ii) the maintenance of fishing boats. This predominantly primary-data-based approach, supplemented with only two carefully selected secondary data, was adopted to ensure robustness, precision, and accuracy of the study. Table 1 presents the input flows used to model mussel production at the La Spezia facility.

2.2.2.2. Allocation. The facilities of the Cooperativa Mitilicoltori Spezzini are primarily dedicated to mussel production, but in recent years some members have also started oyster production to diversify activities and respond to growing market demand. In 2022, the facility produced 2700 tons of mussels and 30 tons of oysters. Given this multifunctional system, where the two productions are physically distinct with separate final products, it was decided to allocate the inputs. This procedure ensures an optimal distribution of resources and accurately reflects the contribution of each production within the cooperative's overall system.

Allocation is necessary only for the energy inputs related to the purification phase, as it is the only process shared by the two productions (Ekvall and Finnveden, 2001). It is not needed for other processes such as those related to materials used, boats, or the use of vibrating sieve machines, as the two productions have separate lines. Among the different types of allocation, it was decided to proceed with mass allocation. In this context, more tons of material to be purified correspond to

Table 1
Life Cycle Inventory (LCI) of the mussel farming system, based entirely on primary data collected through interviews, on-site observations, and company records, including inputs of raw materials, energy, and processes for each life cycle stage.

Materials	Quantity	Unit Of Measure
High-density polyethylene tubolar nets	6335	Kg
Polyethylene bags	7584.5	Kg
Polypropylene nets	7584.5	Kg
Packing cardboard for nets	208	Kg
Latex Gloves	18	Kg
Nitrile Gloves	50	Kg
Packing cardboard for Gloves	20	Kg
Polypropylene labels	410	Kg
Packing cardboard for Labels	37	Kg

Transport	*Quantity*	*Unit Of Measure*
Average distance between mussel cultivation farm and mussel nurseries	5	Km
Annual distance between mussel cultivation and mussel farm (Transport by boat)	9600	Km
Average distance between Galicia production site and mussel farm in La Spezia	3866	Km
Annual distance between Galicia production site and mussel farm in La Spezia (Refrigerated road transport)	65,722	Km
Average distance between the shell waste collection plant and the mussel farm in La Spezia	384	Km
Annual distance between the shell waste collection plant and the mussel farm in La Spezia (Road transport)	20,023	Km
Average distance between the plastic waste collection facility and the mussel farm in La Spezia	44	Km
Annual distance between the plastic waste collection plant and the mussel farm in La Spezia (Road transport)	582	Km
Average distance between plastic net seller and mussel farm in La Spezia	346	Km
Annual distance between plastic net seller and mussel farm in La Spezia (Road transport)	2768	Km
Average distance between tubular net seller and mussel farm in La Spezia	642	Km
Annual distance between tubular net seller and mussel farm in La Spezia (Road transport)	12,840	Km
Average distance between label seller and mussel farm in La Spezia	334	Km
Annual distance between label seller and mussel farm in La Spezia	2672	Km

Machine	*Annual Energy Consumption*	*Unit Of Measure*
Vibrating screen machine	44,928	KWh
Purification plant	84,096	KWh
Cooling Unit	92,160	KWh
Packaging machine	14,976	KWh
Cold Storage	34,560	KWh
Auxiliary energy consumption	37,443	KWh

higher energy consumption and longer plant utilization times. Following the guides of ISO 14044, the mass-based allocation was made considering the quantity of mussels and oysters produced by the Spezzini Mussel Farmers Cooperative in 2022.

2.2.3. ScenarioAnalysis

To frame the study within a more comprehensive evaluation and better address the issues related to the impacts of mussel farming, three alternative scenarios have been implemented compared to the current one (Scenario A). In Scenario B, it was assumed that the entire energy requirement of the mussel farming activity would be met by renewable sources instead of fossil fuels. Specifically, the local installation of photovoltaic panels of 300 kW was foreseen. This hypothesis is supported by the recent project of the cooperative intending to install such panels on its roof. In Scenario C, on the other hand, a 50 % reduction in the importation of foreign products was hypothesized. Finally, in Scenario D, the study was conducted by reducing the importation of products by 100 %. Although hypotheses C and D do not reflect the current choices of the company, it was considered useful to keep them as a reference to evaluate the potential mitigation of environmental impacts.

3. Results

3.1. Life cycle impact assessment (LCIA)

The results of the Life Cycle Assessment (LCA) applied to mussel farming, with particular attention to the environmental impact indicators (LCIA), are shown in Figs. 2 and 3. The allocation of shared energy consumption during the depuration phase was based on the mass of the final products. This choice is motivated by the fact that the production of the two products is physically separated and the only shared input is the energy consumed. By applying mass allocation to a total energy consumption of 176,256 kWh, using the proportions calculated in Table 2, the distribution of energy consumption is as follows:

Mussels: 0.99* 176,256 = 174,493.44 kWh
Oysters: 0.01 * 176,256 = 1762.56 kWh

The results are displayed in terms of characterization (Fig. 3) and subsequently normalization (Fig. 4). The characterization phase allows for the quantification of impacts in specific units for each category, providing a direct measure of emissions and resource consumption. To visualize the characterization results in a single graph, the values were expressed as percentages. The normalization phase, on the other hand, allows these impacts to be compared on a common scale, facilitating the interpretation of results and their comparability against a standardized reference without units of measurement. The results are expressed on a logarithmic scale on the ordinate axis. This choice makes smaller values more visible, preventing them from being compressed by higher values.

By analyzing the relative contributions, it can be observed that in all 11 impact categories, the main contribution is attributable to the farming phase, which accounts for over 90 % in 10 of the 11 categories. The normalization results show that the impact category "Marine Ecotoxicity" is where the farming phase has significantly greater weight. In Fig. 5, the "Farming" phase was investigated with specific focus since it is among the once generating the higher impacts. It becomes clear that almost all of the impacts from "farming" are due to mussels imported from abroad. In this study, the “Imported Product” process refers exclusively to the refrigerated road transport of mussels from Galicia to La Spezia, modeled through the ecoinvent database, which already accounts for the use of refrigerants such as R-134a. In Fig. 6, analyzing the normalized values confirms that the marine ecotoxicity category is the most involved.

3.2. Scenario analysis results

The scenario analysis was conducted to evaluate the environmental impacts of mussel farming in La Spezia through the implementation of four different configurationss.

- Scenario A (current situation);
- Scenario B (use of renewable energy sources);
- Scenario C (50 % reduction in the import of foreign products);
- Scenario D (total elimination of the import of foreign products).

The environmental impacts were measured and expressed across 11 impact categories, representing various environmental aspects and consequences related to mussel production. The obtained values refer to the Functional Unit chosen for the study, which is the annual mussel production for the year 2022. These values are reported as total impacts, derived from the sum of the contributing processes included within the system boundaries. For each impact category considered, the results are detailed in Table 3, showing the characterization values for each of the four analyzed scenarios. This breakdown allows for a clear comparison

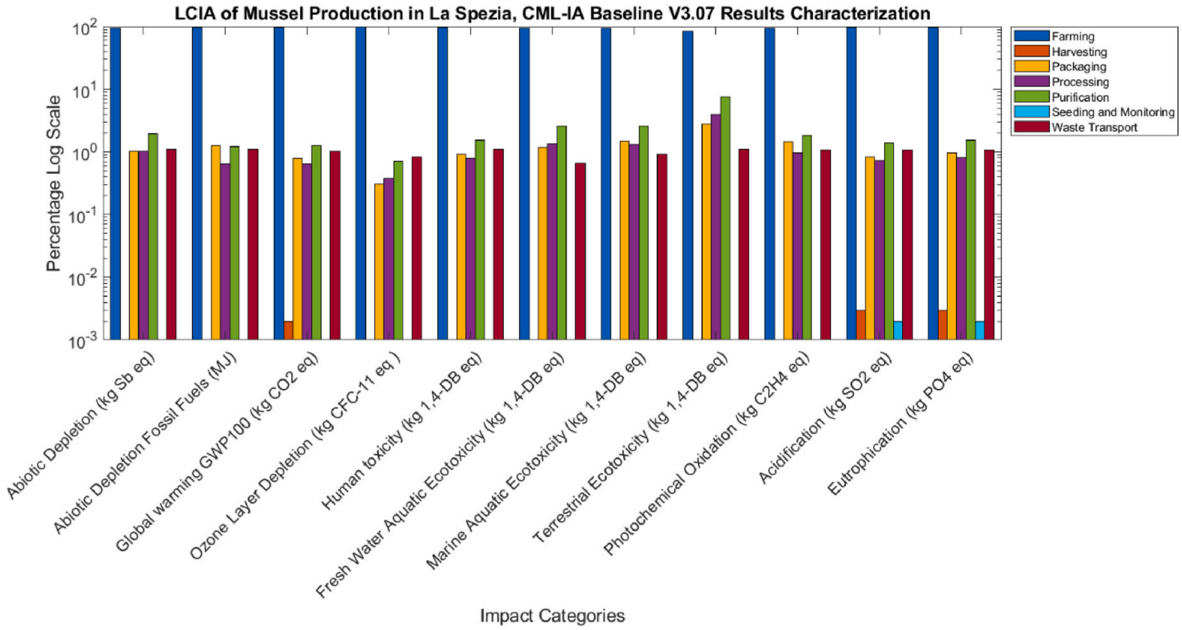

Fig. 3. Characterization results of the Life Cycle Assessment (LCA) according to 11 impact categories of the CML-IA Baseline method, version 3.07. The y-axis is presented on a logarithmic scale.

Table 2
Mass-based allocation percentages for shared processes.

Mussels	Oysters
2700t/2730t = 0.99 (99 %)	30t/2730t = 0.01 (1 %)

of the effects of each scenario, highlighting the differences and potential reductions in environmental impacts achievable through specific modifications to production processes and energy supply sources.

In Table 4, the impact reductions of Scenarios B, C, and D compared to scenario A are reported as percentage differences for each impact category. This representation allows for a quick understanding of the extent of the environmental impact reductions resulting from the implementation of the alternative scenarios compared to the current situation, thereby facilitating the identification of the most effective strategies to reduce the production hotspots of mussel farming in La Spezia.

Fig. 7 shows the four scenarios evaluated in the study, aiming to identify how the weight of processes within the system boundaries changes depending on the scenario considered.

3.3. *Results relating to 1 ton of product*

To facilitate data interpretation and comparison with the results of

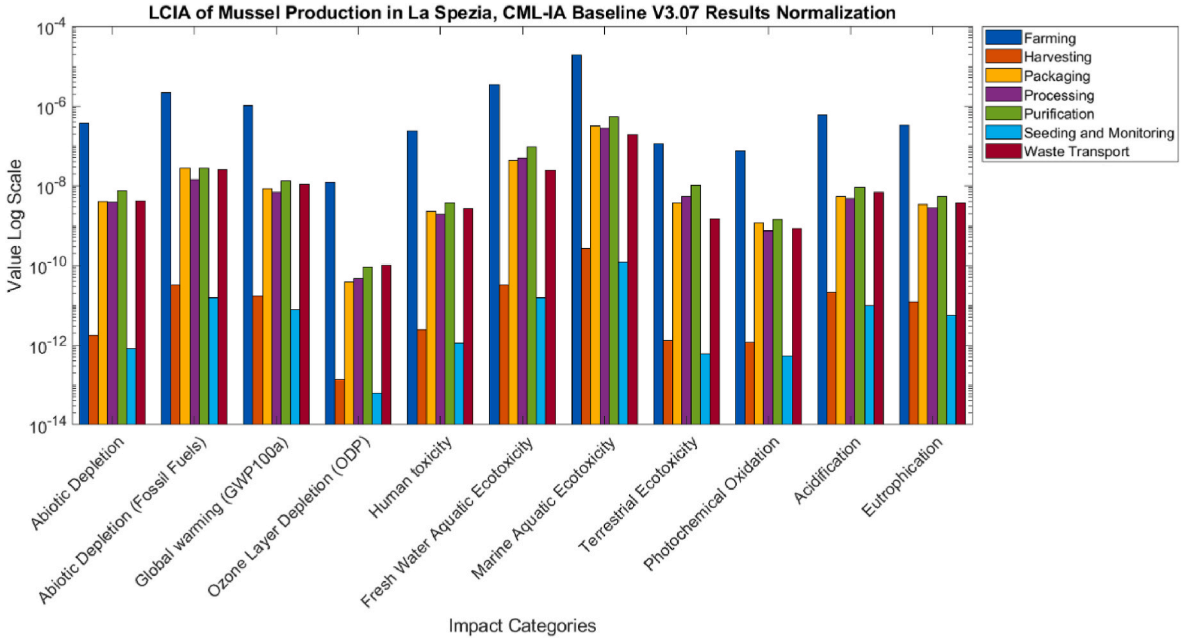

Fig. 4. Normalization results of the Life Cycle Assessment (LCA) according to 11 impact categories of the CML-IA Baseline method, version 3.07. The y-axis is presented on a logarithmic scale.

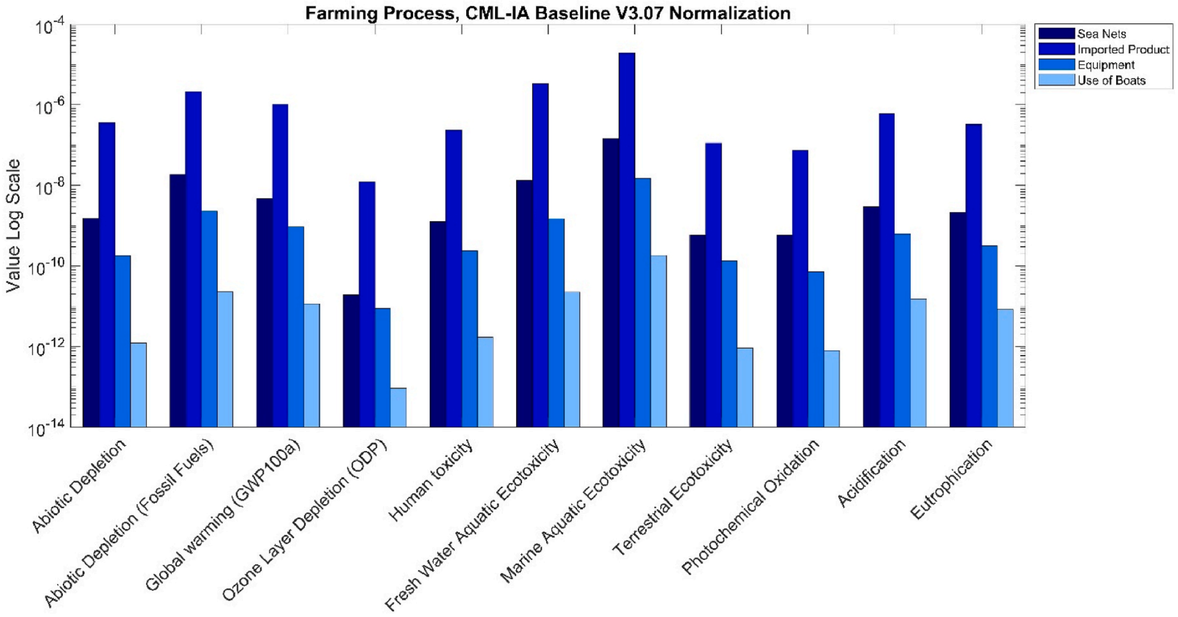

Fig. 5. Characterization results just for the 'Farming' phase according to the CML-IA Baseline method, highlighting the contributory processes. The y-axis is presented on a logarithmic scale.

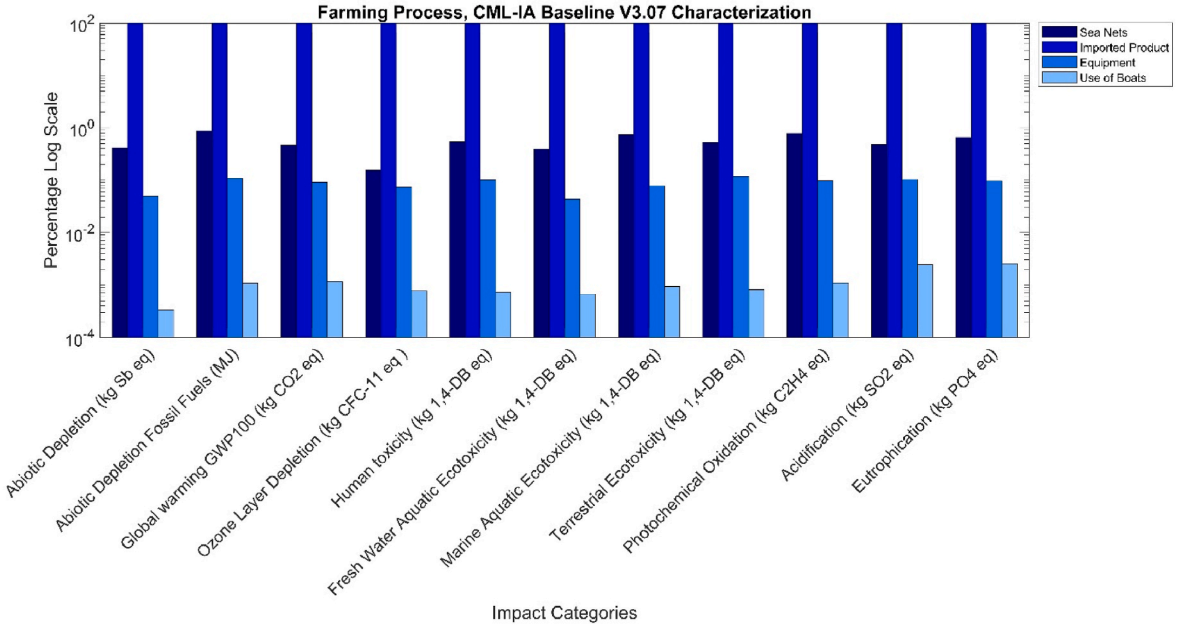

Fig. 6. Normalization results just for the 'Farming' phase according to the CML-IA Baseline method, highlighting the contributory processes. The y-axis is presented on a logarithmic scale.

other studies, the environmental impact results in Table 5 have been also expressed with reference to 1 ton of product.

4. Discussion

4.1. Hotspot interpretation

From the results of the Life Cycle Assessment on mussel farming in La Spezia, it is evident that one of the major environmental impact factors is due to the refrigerated transport of mussels from Galicia to La Spezia. This transportation method, necessary to maintain the product's freshness during the long journey, results in significant greenhouse gas emissions. The vehicles used not only travel long distances but also need to maintain low temperatures to preserve the mussels' organoleptic qualities. The need to receive mussels from abroad is mainly due to seasonality: mussels farmed in Italy have a production cycle that makes them available primarily from May to October, whereas importing from Spain allows for a more consistent and continuous supply regardless of the season. In Galicia, different techniques and environmental conditions for mussel farming enable year-round production, making Spain not only one of the world's largest producers but also one of the main exporters.

Figs. 4 and 5 clearly show that the Marine Ecotoxicity impact category is where the environmental impacts are most concentrated. This

Table 3
Numeric variation across the four scenarios studied for the 11 impact categories, including Abiotic Depletion (AD), Abiotic Depletion of Fossil Fuels (ADf), Global Warming Potential over 100 years (GWP100), Ozone Layer Depletion (ODP), Human Toxicity (HT), Fresh Water Aquatic Ecotoxicity (FWAE), Marine Aquatic Ecotoxicity (MAE), Terrestrial Ecotoxicity (TE), Photochemical Oxidation (PO), Acidification (Acid.), and Eutrophication (Eutroph.). The graph highlights the relative differences between scenarios in terms of characterization of environmental impacts.

Impact Cat.	Unit	Scenario A	Scenario B	Scenario C	Scenario D
AD	kg Sb eq	31.9	30.7	16.7	1.4
ADf	MJ	69,319,282.9	67,746,477.8	36,079,396.0	2839509.1
GWP100a	kg CO2 eq	5,202,307.1	5,082,003.9	2,685,931.8	169,556.5
ODP	kg CFC-11 eq	1.1	1.1	0.6	0.02
HT	kg 1,4-DB eq	1,853,986.6	1,801,887.2	962,959.1	71,931.7
FWAE	kg 1,4-DB eq	1,856,186.2	1,767,570.2	979,735.1	103,283.9
MAE	kg 1,4-DB eq	2,382,182,045.0	2,269,383,936.0	1,265,116,330.4	148,050,618.1
TE	kg 1,4-DB eq	6398.0	5498.2	3679.3	960.6
PO	kg C2H4 eq	656.1	633.8	344.9	33.7
Acid.	kg SO2 eq	17,638.7	17,180,6	9133.7	628.6
Eutroph.	kg PO4 eq	4463.8	4336.5	2323.1	182.4

Table 4
Percentage variation across the four scenarios studied for the 11 impact categories. The graph highlights the relative differences between the scenarios in terms of normalization of environmental impacts.

Impact Category	Unit	Variation A-B %	Variation A-C %	Variation A-D %
Abiotic depletion	kg Sb eq	−3.76	−47.65	−95.61
Abiotic depletion (Fossil Fuels)	MJ	−2.27	−47.95	−95.90
Global Warming Potential 100	kg CO2 eq	−2.31	−48.37	−96.74
Ozone layer depletion	kg CFC-11 eq	0.00	−45.45	−98.18
Human toxicity	kg 1,4-DB eq	−2.81	−48.06	−96.12
Fresh water aquatic ecotox.	kg 1,4-DB eq	−4.77	−47.22	−94.44
Marine aquatic ecotoxicity	kg 1,4-DB eq	−4.74	−46.89	−93.79
Terrestrial ecotoxicity	kg 1,4-DB eq	−14.06	−42.49	−84.99
Photochemical oxidation	kg C2H4 eq	−3.40	−47.43	−94.86
Acidification	kg SO2 eq	−2.60	−48.22	−96.44
Eutrophication	kg PO4 eq	−2.85	−47.96	−95.91

phenomenon is mainly attributable to the use of refrigerant liquid in transport vehicles, such as R-134a (Tetrafluoroethane). The use of this type of refrigerant, necessary to maintain low temperatures during transport, significantly contributes to marine ecotoxicity due to its harmful chemical properties. As mentioned in section 2.2.2, an important aspect of mussel farming concerns the production and use of plastic materials, not only for the nets used in mussel farming but also for the bags used for their final packaging. The use of these plastic nets is a common practice in aquaculture due to their durability and cost-efficiency; however, these same nets often end up being dispersed into the sea, significantly contributing to marine plastic pollution (Apete et al., 2024). Abandoned or lost nets during farming operations degrade slowly, releasing microplastics, which pose an increasing threat to aquatic biodiversity and can enter the food chain, with potential consequences for human and animal health (Simantiris et al., 2024). For this reason, since 2021, the cooperative Mitilicoltori Spezzini has been a partner in the LIFE Muscles project, which aims to contribute to reducing the impact associated with the use of polypropylene (PP) socks by creating more sustainable value chains that minimize their dispersion in the marine environment (LIFE MUSCLES, 2021). The project encourages the recovery and recycling of polymers for the production of new socks and other items. It is important to note, however, that although plastic pollution and the release of microplastics are recognized as major environmental problems, quantifying them remains complex. Not only is there a scarcity of data, but there are also difficulties in reliably attributing waste to a specific geographical area or a particular aquaculture activity (Ruiz et al., 2021). For this reason, these flows have not been included within the system boundaries in this study. This limitation also reflects the current LCA methodology, there is no indicator in the LCA methodology that specifically quantifies the impacts of microplastics in the sea, which is why it does not emerge as a direct environmental hotspot in Figs. 4 and 5. The growing concern about these impacts has led to several studies and research efforts focused on developing an indicator related to microplastics, but to date, this absence in the LCA methodology prevents a comprehensive assessment (Sabate and Kendall, 2024; Woods et al., 2021).

4.2. *Evaluations on Scenario analysis*

The scenario analysis highlights that different strategies may lead to very different outcomes in terms of environmental performance. While Scenario B, based on the adoption of renewable energy, shows only modest improvements (2–4 %), it still represents a relevant step because it is feasible, already under implementation, and consistent with broader decarbonization strategies in aquaculture. This result is coherent with the initiatives currently undertaken by the Cooperativa Mitilicoltori Spezzini, which is installing a photovoltaic plant on the roof of its facility, further demonstrating the commitment of local producers to energy transition and environmental improvement. This indicates that energy-related measures, although secondary to other drivers, can contribute to climate mitigation and improve the overall sustainability profile of the sector.

Much larger improvements are associated with scenarios that reduce the dependence on imports (Scenarios C and D). Cutting imports by 50 % (Scenario C) reduces impacts by more than 40 % across all categories, emphasizing that transportation and supply chains are in this case the main levers for environmental optimization. Although Scenario D, based on the complete elimination of imports, is unrealistic in the short term, Scenario C can serve as a concrete driver for moving toward more localized farming practices. This would require a greater focus on larval capture and seed collection, as well as the implementation of strategies to enhance local production capacity. While a complete transition may not be immediately feasible, incremental progress in this direction could significantly improve environmental performance and resilience.

Overall, the scenario analysis not only quantifies potential reductions but also provides guidance on the prioritization of interventions. The results indicate that energy-related actions, such as photovoltaic installations, can contribute not only to energy efficiency but also to reducing impacts across the analyzed categories. In this context, Scenario C represents a realistic and feasible pathway, while Scenario D remains a theoretical benchmark of maximum reduction. Taken together, these findings suggest that combining incremental

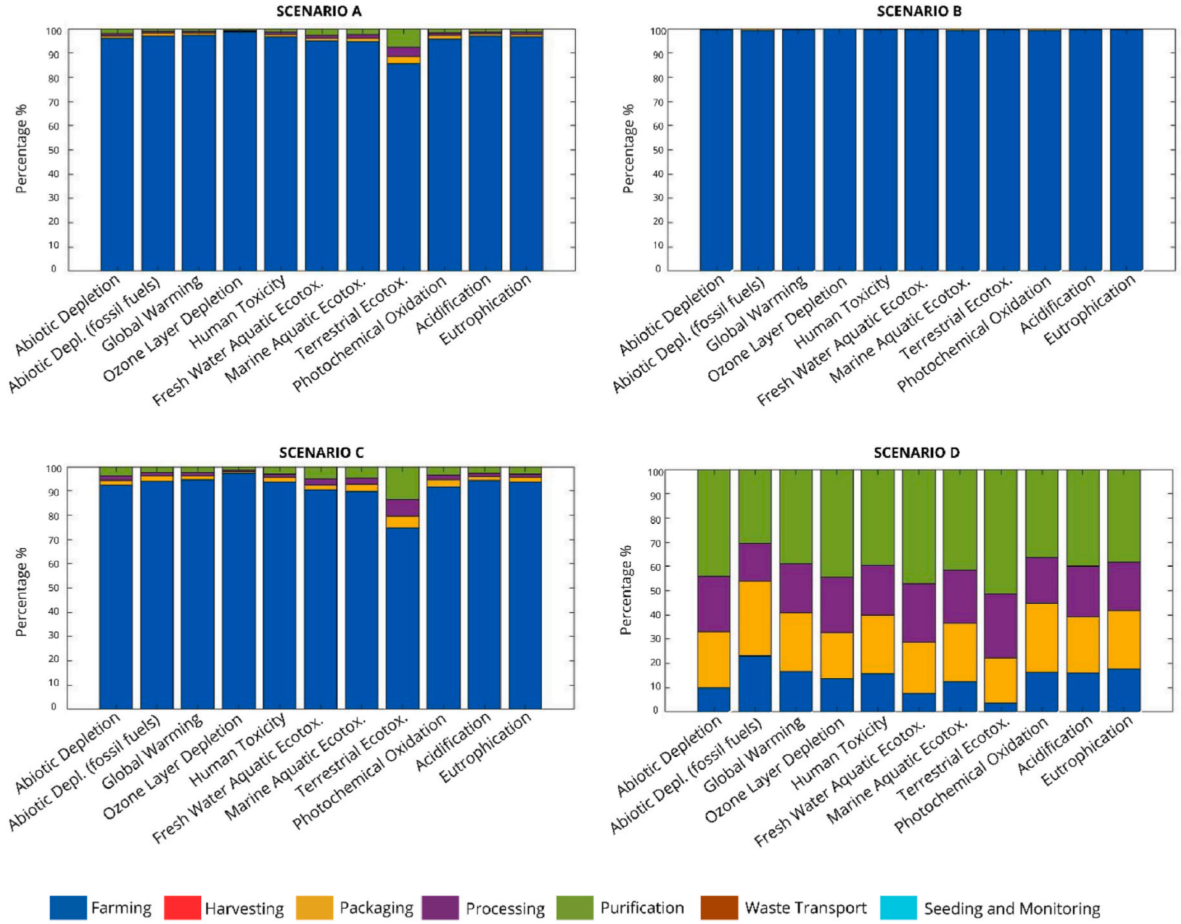

Fig. 7. Characterization results (%) of the LCA analysis according to the Impact Categories of the CML-IA Baseline method, version 3.07, for the four scenarios studied. Scenario A (current situation), Scenario B (use of renewable energy sources), Scenario C(50 % reduction in the import of foreign products), and Scenario D (total elimination of the import of foreign products).

Table 5
Characterization Results of Environmental impact for mussel farming in La Spezia, expressed per 1 ton of product.

Impact Cat.	Unit	Impacts related to FU	Impacts per 1 ton
AD	kg Sb eq	31.9	0.01
ADf	MJ	69,319,282.9	25,673.81
GWP100a	kg CO2 eq	5,202,307.1	1926.78
ODP	kg CFC-11 eq	1.1	0.00
HT	kg 1,4-DB eq	1,853,986.6	686.66
FWAE	kg 1,4-DB eq	1,856,186.2	687.48
MAE	kg 1,4-DB eq	2,382,182,045.0	882,289.65
TE	kg 1,4-DB eq	6398.0	2.37
PO	kg C2H4 eq	656.1	0.24
Acid.	kg SO2 eq	17,638.7	6.53
Eutroph.	kg PO4 eq	4463.8	1.65

improvements with structural changes toward greater local self-sufficiency can lead to substantial progress in the sustainability of mussel aquaculture, offering insights that are relevant beyond the specific case of La Spezia.

4.3. Carbon stock and contributions to circular economy

Mussel farming has the potential to offer significant benefits to the circular economy through the reuse of shell waste, which is primarily composed of calcium carbonate ($CaCO_3$), a mineral compound with multiple industrial applications (Currey, 1999). These shells, once recovered, can serve as a secondary raw material in various sectors, including the construction industry, where ground shells can be used in cement and bituminous compounds, reducing dependency on non-renewable resources (Eziefula et al., 2018). Exploring the opportunities for reusing these materials from a circular economy perspective further reduces the environmental impact of mussel farming by eliminating some of the impacts related to waste transportation to management facilities (Morris et al., 2019). Additionally, this can generate new local economic opportunities and reduce the need to extract new natural resources, such as limestone, thereby decreasing the environmental impact associated with extractive activities (Barros et al., 2021; Caroscio et al., 2024).

Mussel shells represent a significant resource not only for their industrial reuse but also as carbon stocks (Jansen and van den Bogaart, 2020). This carbon storage capacity becomes particularly relevant in the context of climate change and sustainable natural resource management (Suplicy, 2020b; Vaughn, 2018b). The calcium carbonate in the shells results from the atmospheric carbon fixation by mussels during their life cycle. However, the idea of considering mussel shells as significant carbon stocks is still under debate within the scientific community (Munari et al., 2013). Research in this field is progressing, with recent studies providing insights that help to better understand the potential benefits and limitations of this practice.

By limiting the volume of shells destined for landfills, reducing the extraction of raw materials, and analyzing the potential of shells as carbon stocks, mussel farming can become an example of how productive activities can support sustainable development through the circular use of resources.

4.4. Upcycling of mussel shell management

At present, mussel shells can fall under two main regulatory frameworks: they may be managed as waste according to the EU Waste Framework Directive, or as by-products. Specifically, when considered as by-products, they are regulated as category 3 animal by-products under Regulation (EC) No 1069/2009. Although classified as low-risk, they must be treated in specific facilities to ensure they do not pose a danger to human or animal health. This rigorous control limits the ways in which shells can be reused, restricting their use to sectors that can ensure compliance with health and environmental regulations.

When treated as waste, the prevailing end-of-life option is landfill disposal, which represents the lowest tier of the EU waste hierarchy and entails a complete loss of material value. When managed as ABPs, shells can be used for the production of animal feed, pet food, or fertilizers. However, this represents a form of downcycling, as it does not fully exploit their high calcium carbonate content and limits their potential for higher-value applications.

From a circular economy perspective, mussel shells, given their high calcium carbonate content, fit well into valorization processes within the framework of the blue circular economy. At the European scale, this potential could be unlocked by developing specific end-of-waste criteria that recognize shells as secondary raw materials rather than waste, thereby expanding their market applications. At the local scale, and in particular within the Liguria region, shells could instead be managed as by-products, in line with regional regulations on secondary materials, enabling their integration into local value chains. The local pathway is certainly simpler and more immediate from a regulatory perspective, although with a more limited impact compared to the broader benefits that could be achieved through an EU-wide End-of-Waste designation.

5. Conclusion

The sustainability of food production is an increasingly relevant topic in contemporary discussions (Domingo-Morcillo et al., 2024; Vargas et al., 2021). The issue of mussel importation intersects with seasonality, fitting into a broader context related to the large-scale distribution's need for a continuous supply of products, often with little attention to seasonality. Promoting the production and consumption of locally sourced food, emphasizing seasonality and territorial provenance, proves to be a virtuous practice (Wallnoefer et al., 2021). This approach helps build more sustainable food systems, with tangible benefits for both the environment and local communities, reducing environmental impact and supporting local economies. It is evident that long-distance transportation exacerbates the overall environmental impact of the supply chain, making it essential to find more sustainable alternative solutions.

The analysis of alternative scenarios has shown that the adoption of renewable energy sources can also significantly reduce environmental impacts. In this perspective, the work of the Cooperativa Mitilicoltori Spezzini, which involves the installation of solar panels on the structure's roofs and a commitment to recycling and reusing plastic nets, highlights business choices in line with the adoption of environmental strategies identified in this research. Equally relevant is the potential valorization of mussel shells, which can further contribute to circular economy strategies and strengthen the overall sustainability of the supply chain.

This work provides a solid decision-making tool aimed at improving the sustainability of mussel farming in La Spezia. The collected evidence suggests that a systemic approach, considering seasonality, territorial provenance, the adoption of sustainable technologies, and the valorization of waste, can make the entire mussel farming supply chain up to the challenges of our times.

5.1. Future research directions

The life cycle analysis of mussel farming in La Spezia offers ample opportunities for future research and practical improvements. A necessary step involves the inclusion of economic analyses of the various proposed scenarios, thereby expanding the discussion not only to environmental needs but also to the feasibility and economic benefits.

Simultaneously, from a methodological perspective, it would be interesting to enrich the LCA analysis with environmental impact indicators related to the release of plastics and microplastics into the sea, thus obtaining a more comprehensive environmental perspective.

Within the LCA analysis, it would also be appropriate to integrate considerations of mussels as a source of carbon stock. This approach would consider the contribution of mussel farming to climate change mitigation by considering mussel shells as a valuable resource for carbon sequestration.

Finally, by adopting an end-of-life criterion and a circular economy approach to valorize the shells from mussel farming in La Spezia, a qualitative and quantitative assessment of waste along the seven production areas of the gulf could be carried out. By proposing a management agreement not only with mussel farmers but also with local restaurants and municipal entities, a single storage point for the shells could be created, enabling coordinated management of this new resource and laying the groundwork for large-scale valorization pathways in line with the blue circular economy.

CRediT authorship contribution statement

Letizia Caroscio: Writing – original draft, Investigation, Data curation, Conceptualization. **Cristian Chiavetta:** Writing – review & editing, Validation, Methodology, Conceptualization. **Alessandra Bonoli:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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