UNIVERSITÀ DEGLI STUDI DI MILANO

PhD Course in Environmental Sciences

XXXVII Cycle

Department of Environmental Science and Policy

Mediterranean aquaculture and sustainability: holistic assessment of European Sea bass (*Dicentrarchus labrax*) and Gilthead Sea bream (*Sparus aurata*) farming

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Academic Year 2023/2024

Abstract

Aquaculture is one of the fastest-growing sectors globally and is increasingly recognized as a primary solution to meet the rising global demand for seafood. This trend is also present in the Mediterranean region, where two of the most important species in terms of both production and economic value are European Sea Bass (*Dicentrarchus labrax*) and Gilthead Sea Bream (*Sparus aurata*). These two species are typically farmed both in coastal sea cages and land-based systems. Both methods, while effective for large-scale production, present distinct challenges related to environmental concerns, including energy consumption, resource use, nutrient discharge, biofouling, and feed-related emissions.

The central goal of this thesis is to provide a comprehensive assessment of the environmental performance of different aquaculture systems using Life Cycle Assessment (LCA) methodology. Through this approach, the thesis aims to identify key hotspots in aquaculture production, analyse potential strategies for mitigating environmental impacts, and explore innovative farming technologies such as Integrated Multi-Trophic Aquaponic systems (IMTAcs). The overarching objective is to evaluate the environmental footprint of aquaculture systems and suggest pathways for improvement, particularly by optimizing energy use, feed efficiency, and infrastructure design. A multi-criteria decision analysis (MCDA) model was also applied to a case study with the aim of providing a comprehensive sustainability assessment.

This thesis is divided into three main sections each incorporating scientific studies that focus on different aspects of the environmental impact of Sea Bass and Sea Bream farming in the Mediterranean region.

Chapter 3 offers an in-depth analysis of the current environmental performance of Sea Bass and Sea Bream farming, including a review of published LCA studies, comparisons between farming systems, and energy analysis. The first step of this work was to review existing LCA studies on the farming of Sea Bass and Sea Bream in the Mediterranean, summarizing and comparing the main results, identifying environmental impact hotspots, and pointing out methodological concerns. The review revealed that feed production is the most significant contributor to environmental impacts, particularly regarding greenhouse gas emissions and resource use. Additionally, most studies have employed a mass-based functional unit and "cradle-to-gate" boundary. This study also highlighted gaps in

geographic representation and transparency in data reporting and underscored the need for overall sustainability assessments. Following the review, a comparison of different farming systems, including traditional sea cages and land-based systems, was performed. The results indicated that sea cage systems have lower environmental performance compared to land-based facilities, as the latter require substantial energy inputs for water pumping, filtration, and aeration. Also the energy analysis confirmed that coastal sea cages benefit from lower direct energy consumption but still face challenges related to the production of feed, which remains the dominant factor in overall environmental impacts. This chapter provides a baseline understanding of the environmental challenges associated with Mediterranean aquaculture and serves as a foundation for exploring potential mitigation strategies in the following sections.

Chapter 4 focuses on two potential strategies to mitigate the environmental impact of Sea Bass and Sea Bream aquaculture. The first strategy explored is an innovative Integrated Multi-Trophic Aquaponic system (IMTAcs), which integrates fish farming with the cultivation of detritivorous filter-feeding organisms (such as mussels, clams, and polychaetes) and halophytic plants like Salicornia. The idea behind this system is to create a closed-loop where the waste from fish farming becomes a resource for other organisms in the system, thereby reducing nutrient emissions and minimizing the need for external feed inputs. The environmental performance of IMTAcs was assessed using an ex-ante LCA approach, given the experimental nature of the pilot system. Two scenarios were modelled: one using an alternative feed (composed by mussels, clams and polychaetes) and the other using traditional commercial feed. The results showed that while electricity consumption remained a major driver of environmental impacts, leading to higher environmental performance in many impact categories, IMTAcs demonstrated a strong potential to mitigate eutrophication and nutrient discharge. The integration of detritivorous and plants effectively reduced nutrient outflows compared to traditional monoculture fish farming. However, certain limitations were noted, such as the low Technology Readiness Level (TRL) of the system and the challenges in scaling up this model for commercial use. The second strategy evaluated was the use of copper alloy nets in sea cages, replacing traditional nylon or polyethylene nets. Copper alloy nets have longer lifespans and are less prone to biofouling, which reduces the need for antifouling chemicals and frequent maintenance. The environmental benefits of using copper nets were assessed, showing that their durability and recyclability could lead to some trade-offs in certain categories. However, the initial cost and recycling process remain challenges for broader adoption.

Chapter 5 extends the sustainability evaluation by incorporating a multi-criteria decision analysis (MCDA) using the DEXiAQUA model. This holistic approach aims to assess not only the environmental but also the economic and social sustainability of aquaculture systems. The DEXiAQUA model was applied to a land-based Sea Bass and Sea Bream farm, providing a qualitative sustainability score that integrates these three dimensions. The MCDA revealed several trade-offs between environmental, economic, and social aspects.. The holistic evaluation emphasized the need for balanced solutions that address all three pillars of sustainability, highlighting that improvements in one area may come at the expense of another. The DEXiAQUA model proved effective in identifying key sustainability trade-offs and areas for improvement, such as optimizing feed use, enhancing energy efficiency, and improving stakeholder relationships.

The findings of this thesis contribute to a deeper understanding of the sustainability challenges in Mediterranean aquaculture, particularly for Sea Bass and Sea Bream farming. The application of LCA to various farming systems has provided critical insights into the environmental hotspots of aquaculture production, with feed production being the most significant contributor to environmental impacts. While this thesis provides valuable contributions to the field of sustainable aquaculture, further research is needed to refine the methodologies and explore new technologies that can enhance sustainability. Areas for future work include the development of alternative feed ingredients, such as plant-based or insect-based proteins, which could reduce the environmental burden of feed production. Additionally, there is potential for scaling up IMTA systems and incorporating renewable energy sources into aquaculture operations, which could further mitigate environmental impacts. Ultimately, the findings of this thesis underscore the need for continuous innovation and collaboration between researchers, industry stakeholders, and policymakers to ensure the long-term sustainability of Mediterranean aquaculture.

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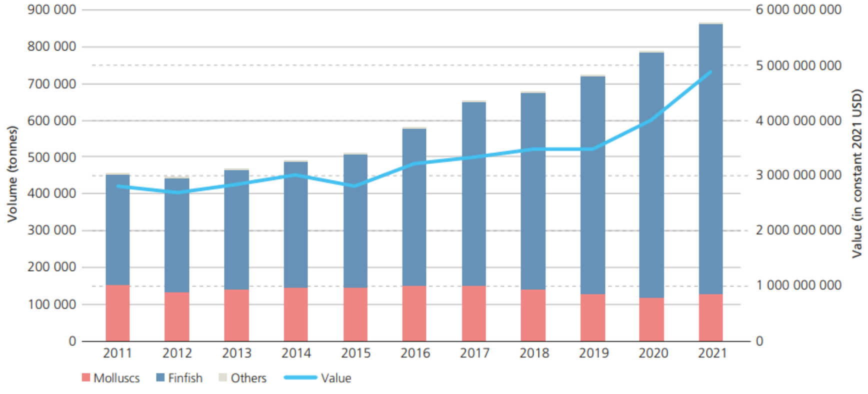
CHAPTER 1 – Introduction

1.1 Brief overview of aquaculture in Mediterranean area with a focus on Sea bass and Sea bream farming

Aquaculture has been steadily increasing its contribution to global seafood production. In 2022, global aquaculture production reached an unprecedented level of 130.9 million tonnes, marking an increase of 8.1 million tonnes from 2020. The estimated farm-gate value of aquaculture products stood at USD 312.8 billion, a rise from USD 278.5 billion in 2020, reflecting the sector's continued expansion and growing importance in global food systems (FAO, 2024). This included 94.4 million tonnes of aquatic animals, valued at USD 295.7 billion, and 36.5 million tonnes of algae, worth USD 17 billion. Additionally, the production of shells and pearls contributed 2,700 tonnes, valued at USD 138.5 million. A significant milestone was reached in 2022 when aquaculture production of animal species, at 94.4 million tonnes, surpassed the global capture fisheries output, which was an estimated 91 million tonnes. This shift signals aquaculture's increasing role in feeding a growing global population and relieving the pressure on wild fish stocks.

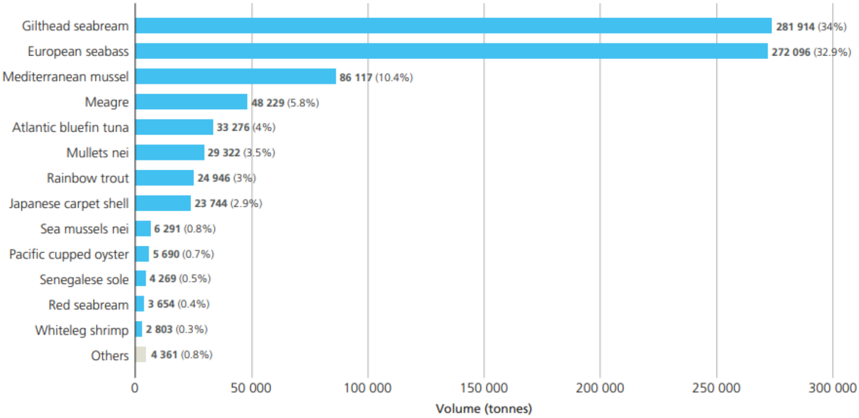
Similarly, aquaculture in the Mediterranean and Black Sea regions has experienced significant growth over the last decade. Marine and brackish water aquaculture in these areas increased production by 91.3% between 2011 and 2021, from 455,000 tonnes to over 870,000 tonnes. This growth was paralleled by a substantial rise in the sector’s economic value, which increased by 74.5%, from USD 2.8 billion to over USD 4.9 billion over the same period (FAO, 2024). The most significant contributors to this expansion have been European Sea bass (*Dicentrarchus labrax*) and Gilthead Sea bream (*Sparus aurata*), two species that are highly valued in the Mediterranean region. In contrast, mollusc production, which accounted for 14.5% of total Mediterranean production in 2021, has experienced a slight decline. Mollusc production averaged 138,000 tonnes annually from 2011 to 2021, with a peak of more than 153,000 tonnes in 2011 and a low of around 119,000 tonnes in 2020. Meanwhile, crustacean production remained modest, contributing only 0.5% of the total production in 2021, equivalent to about 3,600 tonnes. The production of algae, though still minimal, reached over 114 tonnes in 2021, representing 0.01% of total output (figure 1.1).



Note: "Others" refers to algal and crustacean species groups.

Figure 1.1: *Total annual volume and revenue of aquaculture production in the Mediterranean and the Black Sea, 2011–2021 (source: FAO, 2023)*

Sea bass and Sea bream farming, in particular, dominate aquaculture in the Mediterranean region, contributing a significant share to the overall production. In 2020, combined production for these two species reached 520,000 tonnes, with a total market value of USD 2.58 billion (FAO, 2024). Together, Sea bass and Sea bream rank second in the European Union aquaculture sector in terms of value, trailing only Atlantic salmon in economic importance (Llorente et al., 2020). Approximately 95% of the world's production of Sea bass and Sea bream comes from aquaculture, and 97% of this production is concentrated in Mediterranean countries. Turkey is the largest producer, accounting for nearly half of the Mediterranean's production, with approximately 148,000 tonnes of Sea bass and 109,000 tonnes of Sea bream annually. Greece is the second-largest producer, with around 44,000 tonnes of Sea bass and 62,000 tonnes of Sea bream (FishstatJ, 2024). These species are consumed primarily in European markets, particularly in Spain, France, Italy, Greece, and Turkey, where they hold a central place in local diets and regional cuisine.



Note: Percentages indicate the relative contributions of main species reared to total aquaculture production across Mediterranean and Black Sea countries over 2020–2021.

Figure 1.2: *Annual aquaculture production across Mediterranean and Black Sea countries by main species reared, 2020–2021 averages (source: FAO, 2023)*

Historically, aquaculture in the Mediterranean relied on extensive or semi-extensive farming systems that were less intensive than today's methods. In coastal lagoons, wild fingerlings of Sea bass and Sea bream were captured during seasonal migrations and raised in lagoons or enclosed basins. A traditional method known as *vallicoltura*, practiced in Northern Adriatic lagoons, involved rearing fish in large, enclosed areas where water from the sea was allowed to flow in and out. While this system provided a natural environment for fish to grow, it was limited in scale and production output. Over time, technological advancements in aquaculture have shifted farming practices toward more intensive systems, including the use of cages, ponds, and tanks, which allow for greater control over production and higher yields.

Today, Sea bass and Sea bream are primarily raised in more intensive systems, including floating sea cages, raceways, and land-based systems such as ponds and tanks. Cage farming is by far the most commonly used method in the Mediterranean. These cages are open systems that allow for the exchange of water, nutrients, and waste between the cage environment and the surrounding sea. The natural water flow helps regulate water quality inside the cages, reducing operational costs compared to land-based systems. However, this exchange also introduces challenges related to nutrient pollution, disease transmission, and the use of chemicals such as antibiotics and antifouling agents (Cardia & Lovatelli, 2007).

These pollutants can negatively affect the surrounding ecosystems, including the seabed and local marine habitats.

The design and use of sea cages in Mediterranean aquaculture vary depending on the specific characteristics of the farming site. Factors such as wave exposure, seabed conditions, and water depth influence the choice of cage design (Cardia & Lovatelli, 2007). High-density polyethylene (HDPE) cages are the most widely used type in the region due to their flexibility, durability, and low cost. These cages consist of floating rings that support the nets holding the fish, with the entire structure anchored to the seabed using mooring systems. The nets, made from knotless or hexagonal mesh, are periodically replaced throughout the production cycle to prevent biofouling, which can reduce water flow and oxygen availability to the fish (Kalantzi., et al 2016). Sites with high exposure to waves or currents require more robust cage designs and stronger mooring systems to prevent structural damage during storms. Conversely, sheltered sites can use lighter and less costly cage systems, offering greater flexibility and cost savings.

In recent years, there has been increasing interest in land-based systems, particularly Recirculating Aquaculture Systems (RAS), which offer greater environmental control and reduced impact on surrounding ecosystems. RAS technology is an alternative to cage farming and relies on the continuous recirculation and filtration of water to maintain optimal water quality conditions for the fish (Parisi et al., 2014). These systems are typically used in hatcheries, where high-quality fingerlings are produced under controlled conditions before being transferred to grow-out facilities, either in cages or in RAS. The key advantages of RAS include better control over water quality, reduced water use, and improved waste management, as solid waste can be collected and treated before disposal. Additionally, RAS isolates farmed fish from the natural environment, minimizing the risk of disease transmission to wild populations and reducing the reliance on antibiotics and other chemical treatments (Parisi et al., 2014). However, the energy demands of RAS are significantly higher than those of cage farming due to the need for water pumping, filtration, and temperature control. This results in higher operational costs and a larger carbon footprint, limiting its application for large-scale production.

In the Mediterranean, RAS is primarily used for hatchery operations, where fingerlings are grown in controlled environments before being transferred to sea cages for grow-out. The production cycle for Sea bass and Sea bream begins with fingerlings, which are typically produced in hatcheries when they weigh between 2 and 4 grams. These fingerlings represent about 15-20% of production costs, and their quality is critical for ensuring healthy stock and minimizing losses due to disease or poor growth. In cage farming, the production cycle for Sea bream lasts 14-16 months, while for Sea bass it takes slightly longer, around 16-18 months. Fish are harvested when they reach market size, typically between 300-400 grams. During the production cycle, nets of varying mesh sizes are used to accommodate the growth of the fish and prevent biofouling (Cardia & Lovatelli, 2007).

The growing aquaculture sector plays a key role in local economies and food security. In 2021, more than 35,000 aquaculture farms in the region produced about 3.3 million tonnes of aquatic products, employing nearly 350,000 people. The industry provides direct and indirect livelihoods to coastal communities, contributing significantly to economic development and meeting the growing demand for seafood (FAO, 2024). The industry's role in achieving the UN Sustainable Development Goals (SDGs) cannot be underestimated, as it addresses key issues related to global food security, nutrition and sustainable economic growth.

However, as aquaculture production increases, so do concerns about its environmental impact. Nutrient pollution, energy and feed demand and the potential spread of diseases from farmed to wild populations are some of the main challenges facing the industry. These environmental problems highlight the need for more sustainable practices and stricter environmental monitoring. Addressing these problems is crucial to ensure the long-term sustainability of the aquaculture sector and its continued contribution to food security and economic development.

1.2 Aquaculture and environment: the Life Cycle Assessment (LCA) approach for analysing the impact of aquaculture sector

As the aquaculture sector continues to grow, it plays an increasingly crucial role in global seafood production, yet it also faces significant environmental challenges. Among these, cage farming, a prevalent method in marine aquaculture, raises specific concerns due to its open system nature, which involves continuous exchange between the cages and the surrounding water body. This constant interaction leads to a high risk of pollution, in particular the release of nutrients and chemical residues, with an impact on water quality and marine ecosystems (Holmer et al., 2008). Excess nutrients, especially nitrogen and phosphorus, can lead to eutrophication, a process that accelerates algae growth and reduces oxygen levels in the water, causing dead zones that threaten the biodiversity and health of marine habitats. Additionally, conflicts often arise with other coastal area users, particularly the tourism industry, as cage farming operations can influence both environmental aesthetics and water resources. Less than half of the countries in the Mediterranean and Black Sea region have an effective environmental monitoring system for aquaculture activities in place, partly due to poor cooperation between farmers and institutions. Moreover, widely varying regional norms and standards make monitoring of this kind more challenging to organize. In addition to the local pollution effects, aquaculture can have broader environmental impacts. Greenhouse gas emissions arise primarily from energy-intensive activities, especially in land-based systems, which rely on electricity to circulate and filter water, regulate temperatures, and provide aeration (Ayuso-Virgili et al., 2023). This reliance on energy, particularly in regions dependent on fossil fuels, increases the carbon footprint of such systems. Furthermore, the sourcing and production of aquaculture feed contribute significantly to global environmental issues, as many feeds contain fishmeal and fish oil derived from wild fisheries, which places additional pressure on marine ecosystems. The over-exploitation of these resources can lead to the depletion of fish stocks, disrupting marine food chains and reducing biodiversity (Bonhes and Laurent, 2019). However, the production of plant-based feed ingredients, such as soy, often involves land-use changes, deforestation, and the associated emissions of carbon dioxide, making them no less important than other ingredients. (Henriksson et al., 2012).

To address the issue of holistic impact assessment, the Life Cycle Assessment (LCA) methodology has gained prominence as a comprehensive approach to assess the full spectrum of environmental impacts associated with aquaculture. Standardized by ISO 14040 and 14044 standards (ISO, 2006a; ISO, 2006b), LCA evaluates the environmental burdens of a product, process, or system across its entire lifecycle. Originally developed for industrial processes, LCA is increasingly applied to agro-food systems, including aquaculture, providing a detailed framework for assessing multiple environmental indicators such as carbon footprint, eutrophication, acidification, and cumulative energy demand. This allows for a holistic understanding of the environmental impact across the entire supply chain, including feed production, farming practices, processing, and transportation. A key strength of LCA is its ability to simultaneously assess different environmental impacts, helping avoid trade-offs that could occur when one environmental goal is optimized at the expense of another. LCA is typically conducted in four distinct phases (ISO 14040, ISO 14044): (1) Goal and Scope Definition, where the aim, the functional unit and system boundaries are outlined; (2) Life Cycle Inventory (LCI), where all inputs (such as energy, feed, and materials) and outputs (like waste and emissions) are quantified; (3) Life Cycle Impact Assessment (LCIA), where these inventory data are converted into environmental impact indicators; and (4) Interpretation, where the results are analysed and recommendations are made based on the findings.

In LCA, various impact categories are used to evaluate the environmental impacts arising from emissions (e.g., into soil, air, or water) and resource usage (e.g., land, water, energy, and raw materials). Two main types of indicators are identified: problem-oriented categories (mid-point categories), which are more directly linked to environmental interventions, and end-point categories, which focus on broader issues of concern such as human health and natural resource depletion (Guinée et al., 2022). The mid-point approach is more commonly employed due to its simplicity and ease of implementation. Environmental impacts are calculated by multiplying the quantities of emissions and resource consumption by specific characterization factors corresponding to each impact category (Aubin, 2013).

LCA studies have shown that feed production is a critical factor in determining the overall environmental footprint of aquaculture (Aubin, 2013). Feed ingredients, such as fishmeal and plant-based components, are often sourced from agriculture and fisheries, making them resource-intensive. Studies reviewed by Bohnes et al. (2019) emphasize that feed production contributes significantly to climate change impacts, energy use, and land-use change, while the farming process itself is a primary driver of eutrophication due to nutrient runoff into aquatic systems (Ayer et al., 2007). Henriksson et al. (2012) also highlight that the environmental impacts of feed ingredients, especially those derived from wild fisheries or intensive agriculture, can exacerbate issues related to biodiversity loss and overfishing. Both land-based and offshore aquaculture systems present unique environmental trade-offs. Land-based systems, such as Recirculating Aquaculture Systems (RAS), allow for greater control over the farming environment, reducing the risk of direct nutrient discharge into surrounding ecosystems. However, these systems typically require higher energy inputs for water circulation, temperature control, and aeration, leading to increased carbon emissions

(Badiola et al., 2018). In contrast, offshore aquaculture, which involves sea cages, generally reduces energy requirements but presents a higher risk of nutrient pollution and ecosystem disturbance as waste products are directly released into the marine environment. Offshore systems are also more vulnerable to environmental variability, such as currents and storms, which can exacerbate problems like fish escapes and structural damage.

Aquaculture depends on natural resources provided by vulnerable ecosystems and may also impact biodiversity and the ecological functioning of the exploited ecosystems. Moreover, aquaculture increasingly competes with livestock and human populations for agricultural products and the land necessary to grow them, as well as with other human activities such as industry and tourism (Aubin et al., 2019). Beyond pollution and resource depletion, aquaculture poses significant challenges for biodiversity. The farming of non-native species or the escape of farmed species into natural habitats can introduce invasive species, potentially disrupting local ecosystems. These invasive species may outcompete native species for food and habitat, leading to shifts in ecosystem dynamics and even the displacement of indigenous species. This is particularly concerning in regions with sensitive or fragile ecosystems, where such disruptions can have long-lasting ecological effects. Furthermore, the spread of diseases and parasites from farmed to wild fish is a growing issue. Intensive aquaculture systems, especially those with high stocking densities, create environments that are conducive to the proliferation of pathogens. If these pathogens are released into surrounding waters, they can infect wild fish populations, exacerbating biodiversity loss (De Silva, 2012).

In the context of Mediterranean aquaculture, LCA provides a valuable framework for comparing different systems, from intensive land-based operations to extensive and/or intensive offshore farms. It enables a holistic evaluation of their respective environmental trade-offs, such as energy consumption in land-based systems versus nutrient emissions in offshore cages. This approach not only helps identify environmental hotspots but also guides the development of eco-labelling, certification schemes, and policy interventions that promote resource efficiency and minimize ecological damage.

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CHAPTER 2 - Aim and organization of the thesis

2.1. Aim of the work

The main goal of this thesis is to explore the topic of sustainability within the Mediterranean aquaculture sector, specifically focusing on the farming of Sea bass and Sea bream, which represent the two main economically significant species in the region.

The issue of environmental sustainability has been addressed using the Life Cycle Assessment (LCA) methodology. Prior to this thesis, only a few LCA studies had been performed to Sea bass and Sea bream production in the Mediterranean context. Therefore, the first step of this work was to review these studies with the goal of assessing the current knowledge on the environmental performance of these two species farming. Specifically, this included summarizing and comparing the main results of the LCA studies conducted, identifying the aspects of Sea bass and Sea bream farming that are primarily responsible for environmental impacts (hotspot), highlighting key methodological concerns related to LCA application, and suggesting directions for future developments and research.

Additionally, this thesis aims to compare the environmental performance of different farming systems, such as traditional sea cages and land-based facilities, highlighting the main strengths and weaknesses of each farming method. An energy analysis was also conducted for the various farming types using a life cycle approach.

Another key objective of this work was to evaluate innovative solutions and strategies for mitigating environmental impact. To this end, the environmental performance of an innovative aquaponic system was analysed, which combines Sea bass and Sea bream farming with the cultivation of detritivorous filter feeders (such as mussels, clams, and polychaetes) and the growth of Salicornia plants. Additionally, the environmental performance of an hypothetical farming system using copper cages instead of traditional nylon ones was assessed.

Finally, a multi-criteria analysis was conducted using the DEXiAQUA model (Le Feon et al., 2021) to apply a new holistic method for evaluating overall sustainability, which includes environmental, economic, and social aspects. This analysis provided a qualitative sustainability score for a land-based Sea bass and Sea bream aquaculture farm.

2.2. Overview of the chapters

The body of the thesis has been divided into three main chapters related to the three main research activities followed during the doctoral thesis:

- **Chapter 3 - Insight into the current state of environmental performance of Sea bass and Sea bream farming in the Mediterranean area**: this chapter includes four articles that analyse the current state of the application of the LCA methodology, the environmental impact, and the energy demand of the aquaculture sector, through a scientific review and the analysis of several case studies;
- **Chapter 4 - Evaluation of two possible strategies to mitigate the environmental impact of aquaculture:** this chapter includes two scientific articles that analyse two possible alternative solutions to mitigate the environmental impact of aquaculture (an innovative integrated multitrophic aquaponic system and the use of new copper nets for sea cages in sea farming).
- **Chapter 5: Application of a multicriteria model (DEXiAqua) to assess the overall sustainability of aquaculture systems:** this chapter focuses on the application of a new method to assess the overall sustainability of aquaculture farms, integrating environmental, economic, and social sustainability into a single score.

The work, therefore, falls into these three specific fields and, for its development, has focused primarily on the farming of the Sea bass and Sea bream species. In addition to the fact that these species are the two main ones from an economic standpoint for Mediterranean aquaculture, some activities were linked to the PRIMA S2 2018 SIMTAP project "Self-sufficient Integrated Multi-Trophic AquaPonic systems for improving food production sustainability and brackish water use and recycling" (Code 18110-2 SIMTAP), in which the target species were Sea bass and Sea bream. This allowed for the creation of new contacts and networks within the sector, collaboration, and data accessibility thanks to contacts with experts and major companies in the field. Chapters 3 and 4, therefore, consist of a collection of scientific papers produced by the candidate during the doctoral activities, related to the topics described above, while the work reported in Chapter 5 was developed within the aforementioned SIMTAP Project.

Chapter 6, finally, presents a final discussion of the work, drawing general conclusions and setting the pace for further study and improvement.

CHAPTER 3 - Insight into the current state of environmental performance of Sea bass and Sea bream farming in the Mediterranean area

3.1. Scientific article 1: Life Cycle Assessment of Sea bass and Sea bream production in the Mediterranean area: a critical review

Published in: *Aquaculture,* 573 (2023) 739580

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The first step of this thesis was to carry out a literature review regarding the LCA studies published on the farming of Sea bass and Sea bream in the Mediterranean. The paper mainly focused on summarizing the main results of the environmental impacts and hotspots reported by the reviewed studies, as well as the common or divergent methodological choices in applying the LCA methodology. The main findings indicate that the mass-based functional unit is the most commonly used, the "from cradle to gate" perspective to define the system boundaries is the most common, and Global Warming Potential (GWP) is the most studied impact category. However, the review also highlighted the main weaknesses in the study of the environmental impact of this sector, such as geographical representativeness, the standardization of some methodological choices (e.g. functional unit), the lack of transparency in reporting the data used, the omission of some sub-processes such as infrastructure, and the need to expand the vision to a more holistic view of sustainability, including economic and social pillars as well.

3.2. Scientific article 2: Quantification and characterization of the environmental impact of Sea bream and Sea bass production in Italy

Published in: *Cleaner Environmental System,* 9 (2023) 10018

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After conducting the scientific review, the research activity focused on the application of the LCA methodology to several case studies in Italy, since, as highlighted in the previous article, only one Italian facility had been analysed until then. To this end, firstly, an Italian offshore facility was analysed in the present study. In particular, this study primarily focuses on the quantification and characterization of the environmental impact of the production of Sea bream and Sea bass using the Life Cycle Assessment (LCA) approach in a large Italian offshore farm. In this study, the impact was calculated separately for Sea bass and Sea bream, and the average impact of the fish produced was also reported. This was made possible by differentiating the feed conversion ratio (FCR) and the amounts of feed consumed by each species. The main results indicated that Sea bream has lower environmental performance compared to Sea bass. The primary hotspot of impact for this type of farming is by far the feed, with a relative impact reaching over 85% in the Global Warming Potential. However, diesel consumption and infrastructure (e.g., cages and the entire anchoring system) can represent important hotspots in certain impact categories, such as ozone formation or human toxicity. A sensitivity analysis was performed on not-ingested feed and revealed that reducing the lost and non-ingested feed by 50% can reduce environmental impacts by about 5-6%.

3.3. Scientific article 3: Environmental impact of different Mediterranean technological system for European Sea bass (*Dicentrarchus labrax*) and Gilthead sea bream (*Sparus aurata*) farming

Published in: *Aquacultural Engineering,* 107 (2024) 102457

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The research activity included in the SIMTAP Project allowed for outreach to other companies, conducting site visits, and collecting data and information from various production systems. Therefore, the next paper focuses on the environmental performance of four different farms specializing in Sea bass and Sea bream production, all located in Tuscany (Italy). A data collection inventory was completed for two coastal farms, featuring typical offshore sea cages, and two land-based farms, characterized by farming in ponds and tanks. The main purpose of this study was to highlight the strengths and weaknesses of each system and compare different farming facilities. The results showed that coastal farms have lower environmental performance compared to land-based farms. Energy and liquid oxygen consumption are the factors that most penalize land-based farms, compared to offshore farms with low fuel intensity. Sensitivity analysis on the energy sources used revealed that utilizing more renewable energy (as projected by the Italian national electricity mix by 2030) and the use of biodiesel can reduce the environmental impacts of land-based farms for the former and coastal farms for the latter.

3.4. Scientific article 4: Energy analysis in fish aquaculture: cumulative energy demand of different farming systems

Submitted to: *Energy, under review*

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Since previous studies revealed that one of the main hotspots of aquaculture (especially land-based) is energy consumption, whether direct or indirect, and that no in-depth study on the Cumulative Energy Demand (CED) of such systems had been conducted, the next step of the thesis was to carry out a more detailed analysis of the energy demands and cumulative energy consumption of the farms analysed in the previous paper. Therefore, this study focuses on the energy analysis of four Italian aquaculture farms specializing in the production of sea bass and sea bream (two coastal farms and two land-based farms), using a life cycle approach. In this regard, the Cumulative Energy Demand (CED) was calculated, characterized, and compared. The results showed that, as expected, land-based farms have a higher CED compared to coastal farms, and that energy from fossil sources accounts for about half of the CED in all evaluated cases. As the sensitivity analysis indicates, this situation can be improved if the projection of the Italian national electricity mix for 2030 is considered and if a biodiesel fleet is implemented for the management of offshore farming

Abstract

Energy consumption is one of the critical challenges for the continued growth of the aquaculture sector. In addition to the substantial feed consumption common to all types of systems, the high direct energy demand is driven by electricity use for water extraction, pumping, and aeration in land-based farms, and by fuel consumption in coastal farms. The aim of this study is to analyse the Cumulative Energy Demand (CED) of the production of European Sea Bass and Gilthead Sea Bream across different farming systems in the Mediterranean area. By focusing on both land-based and coastal sea-cage systems, an energy analysis of four different farms was conducted using a "from cradle to gate" life cycle approach. The functional unit for this study was set at 1 tonne of fish. The results show that land-based farms have a higher CED (168,535 and 188,642 MJ/t) due to both feed consumption and the use of liquid oxygen and direct electricity (with on-site electricity consumption of 9,491 and 3,913 kWh/t). The lower CED of coastal farms (66,224 and 76,507 MJ/t) is largely due to feed usage (around 90% of the total) and low fuel intensity (67.6 and 82.9 l/t). A sensitivity analysis was conducted on the 2030 projected national electricity mix of the Integrated National Energy and Climate Plan for land-based farms. Additionally, the impact of substituting diesel with biofuel in coastal farms was evaluated. The results indicate that these changes could reduce the use of non-renewable sources by at least 5%.

Keywords

Energy Analysis, Fish farming, Aquaculture Optimisation, European seabass; Gilthead seabream

3.4.1. Introduction

Aquaculture has emerged as a pivotal sector in global food production, contributing significantly to the supply of seafood and playing a vital role in food security (FAO, 2024). The rapid expansion of aquaculture has led to an increased focus on the environmental impacts associated with different farming systems. Among these impacts, energy consumption is a key factor, influencing both the sustainability and economic viability of aquaculture operations (Badiola et al., 2017). Energy use in aquaculture varies widely depending on the type of farming system, the species being cultivated, and the geographical location of the farm (Pelletier et al., 2011; Yi et al., 2024).

In Mediterranean aquaculture, European seabass (Dicentrarchus labrax, ESB) and Gilthead seabream (Sparus aurata, GSB) are two of the most commonly farmed species. Economically, these species are significant, together accounting for 26% of the total economic value of Mediterranean aquaculture, with a combined worth of approximately 3.6 billion USD (FishStatJ, 2024). These species are predominantly raised in either coastal sea-cage systems or land-based facilities, with each system presenting distinct energy requirements. Coastal sea-cage farming is generally considered less energy-intensive due to the reliance on natural water flow for oxygenation and waste removal. In addition, this type of system may also rely on ecosystem services for water quality maintenance. Therefore, typically, the energy consumptions of this type of system are mostly indirect as feed-related energy inputs account for a large proportion of the overall energy profile (Troell et al., 2004); however, fuel consumptions for the management of sea cages cannot be neglected (Pelletier et al., 2011).

In contrast, land-based systems, particularly those employing Recirculating Aquaculture Systems (RAS) or Flow-Through Systems (FTS), often require significant energy inputs for water circulation, aeration, and temperature control. Intensive land-based FTS or RAS are often characterized by substantial energy inputs for activities such as pumping and filtering water. Thus, there are often trade-offs in the nature and extent of environmental impacts associated with open versus closed containment systems. Furthermore, as reported by Henrikkson et al., (2013) there is an expected but imperfect correlation between energy demand and global warming potential, mainly related to feed consumption. Although feed-related energy inputs generally represent a large percentage of the overall energy profile of an intensive livestock system, the absolute scale of these inputs is very sensitive to the specific components of the feed used (Troell et al., 2011).

The cumulative energy demand (CED) of a product is the sum of direct and indirect energy, measured in MJ and consumed during its entire life cycle, including extraction, production and disposal of raw and auxiliary materials used. The total CED is composed of the cumulative demand for fossil energy (i.e. from coal, lignite, peat, natural gas and crude oil) and the CED of nuclear, biomass, water, wind and solar energy over the entire life cycle (Huijbregts et al., 2010).

Despite the importance of energy use in aquaculture, few studies performed the energy analysis of aquaculture systems (Bozoğlu and Ceyhan, 2009; Rahman and Barmon., 2012; Paramesh et al., 2019; Xu et al., 2022) and, specifically, there is a lack of detailed studies focusing on the CED of ESB and GSB production in the Mediterranean region. While some Life Cycle Assessment (LCA) studies have been conducted on these species also evaluating CED impact category (Zoli et al., 2023; Abdou et al., 2018; Aubin et al., 2013), no study specifically addressed the energy dynamics within these systems. Understanding the CED is crucial for identifying opportunities to improve the sustainability of aquaculture practices, particularly in the context of rising energy costs and the global shift towards renewable energy sources.

This study aims to fill this gap by analysing and comparing the CED of ESB and GSB production across different farming systems in the Mediterranean area. By focusing on both land-based and coastal sea-cage farms, this research provides a comprehensive assessment of energy use patterns, highlighting the contributions of various energy sources and identifying potential areas for improvement.

3.4.2. Materials and methods

3.4.2.1. Goal and scope definition

The goal of this study is to analyse in detail the CED of different types of aquaculture farms specializing in the farming of ESB and GSB. Indeed, depending on the type of farming, the energy demand and its characteristics may vary, differ by orders of magnitude, and lead to different outcomes. To build the mass and energy flow characterizing the analysed systems, the Life Cycle Assessment (LCA) approach was applied, following ISO 14040 and 14044 standards (ISO, 2006a, b). This allowed for an in-depth examination of the energy requirements necessary for the farms in question, considering the entire life cycle of all required inputs. This study was conducted on representative ESB and GSB farms in the Mediterranean area and reflects the most traditional farming systems and technologies that characterize the current context of the area of interest. In particular, two coastal farms were analysed, where farming typically takes place in sea floating cages, and the management of the farming process (feeding, disease control, harvesting, etc) is carried out using a fleet of vessels, resulting in fuel consumption. Two land-based farms were also analysed, where fish are typically raised in ponds (either earthen or concrete) characterized by a complex system of generators, pumps, filters, and aerators necessary for water extraction, pumping, oxygenation and flow.

The functional unit (FU) used in the study is 1 tonne of live fish weight, and the approach for defining system boundaries is "from cradle to farm gate." Therefore, all inputs necessary for operations from raw material extraction to fish harvesting were considered. Specifically, as shown in **Figure 1**, the fish farming process was divided into 5 subsystems: (I) raw material extraction and production of inputs common to all subsystems; (II) production and supply of juveniles; (III) production, use, maintenance, and end-of-life of infrastructure and equipment; (IV) production and supply of aquafeed; (V) farm management and fish harvesting.

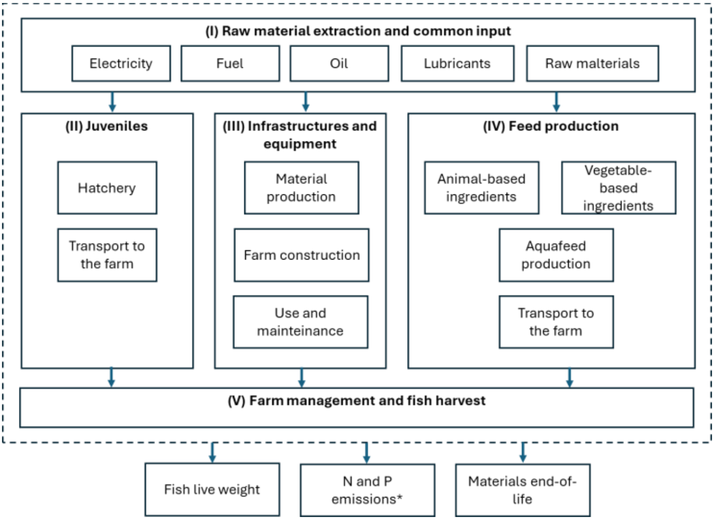

Figure 1: *Figurative representation of the system boundary of this study. *N and P emissions are part of the life cycle of fish production, however they have no impact on CED*

3.4.2.2. Description of the analysed farms

Four Italian farms specialising in ESB and GSB breeding were analysed. To this purpose, on-site visits were made to each of the farms and, initially, information regarding farm description and management was collected. In particular, two land-based (LB1 and LB2) and two coastal-farms (CO1 and CO2) were analysed.

The first land-based farm (LB1) also has a production of about 450 t/fish represented by 53% BSE and 47% GSB. The farm consists of about 60 concrete and GRP tanks, ranging from 30 m^3 to 900 m^3, with a total area of 88,000 m^2. Juveniles of 6 g and 4.5 g are sown for BSE and GSB, respectively. The average Economic Feed Conversion Ratio (eFCR = kg of distributed feed per kg of live fish weight harvested, Aubin et al., 2009) for production is 2.61. This farm, located on the coast, pumps seawater directly into all tanks.

The second land farm (LB2) produces around 450 t/fish (39% ESB and 61% GSB) annually in a total area of 150,000 m^2 with 50 ponds of various sizes, from 75 to 550 m^3. The 3g juveniles are seeded in specific ponds and then transferred to other ponds up to the commercial size of 400-600g. The average eFCR characterising production is 2.4. This farm extracts groundwater from an aquifer at a depth of about 40 metres, which is energy-intensive but guarantees stable temperature, salinity and pathogen-free conditions throughout the year.

The first coastal farm (CO1) analysed is a large Italian farm. The average annual production of the farm is about 1,800 tonnes of fish, divided approximately 50%-50% between ESB and GSB. The farm consists of 32 sea cages of various sizes, with an average of 10,000 m^3 each, located about 4 miles offshore. The eFCR for the year analysed is 2.16, averaged between the two species. Further details on the farm can be found in Zoli et al. (2023b).

The second coastal farm (CO2) has an annual production of about 1,300 t of fish (46% ESB and 54% GSB). It comprises 44 sea cages of different sizes, ranging from 2,000 m^3 to 9,000 m^3, with an average volume of 6,000 m^3, and a total area of about 2,000,000 m^2. Juveniles of 4.5 g and 6 g are seeded to start production and are bred up to a commercial size (400-450 g). The eFCR for the year was 2.86 for ESB and 2.48 for GSB.

3.4.2.3. Life Cycle Inventory

Table 1 shows the data collected for each of the farms analysed in this study. Both primary and secondary data were used for the analysis. Primary data were collected directly from the analysed farms through questionnaires and interviews with the farm's specialist technicians. Specifically, primary data were retrieved for the quantity and size of juveniles seeded; FCR values with the amount of feed given and the percentage of individual ingredients were primary data (supplementary materials, **tables S1-S4).** Primary information was also collected regarding the structure of the farms, with their respective infrastructure and equipment, as described in the previous section: for coastal farms, these data refer to the number of cages used for rearing, their composition in terms of materials, their distance from the coast, their size and the composition of the equipment fleet, including the useful life of all components included in the analysis; for land-based farms, these data refer to the number of tanks or ponds, the pumps required to ensure the required water flow, the filters, the anti-predator net including the useful life of all components included in the analysis; Energy consumption was extrapolated directly from the company's records and concerns the consumption of diesel for boats for coastal farms and the consumption of electricity for land-based farms.

Table 1: *Inventory analysis referring to the production year analysed for each farm*

Main parameters	**LB1**	**LB2**	**CO1**	**CO2**
Production biomass (tonnes)	456	455	1,800	1,340
Mortality rate (%)	20	6.8	14	5.7
Juveniles (tonnes)	5.5	3.8	10.4	22.6
Juveniles average mass (g)	3.5	5.25	2	4.7
Liquid oxygen consumption (kg)	968,000	2,497,266	/	/
Feed (t)	1,130	1,191	3,890	3,506
Energy Inputs				
Electricity (kWh)	4,328,726	1,784,686	23,000	/
Fuel consumption (l)	14,600	6,611	121,700	100,802
Gas consumption (m^3)		/	541	/
Infrastructures (total in the facility)				
Boats (#)	/	/	6	6
Fish cages (#)	/	/	32	44
Ponds (#)	50	63	/	/

Anti-predator net (m^2)	21,000	25,860	/	/

Secondary data obtained from the Ecoinvent V3.9 database (Weideiema et al., 2013) were used to model the impact of raw materials used and fuel production and procurement. For the modelling of individual feed ingredients, secondary data obtained from both the Ecoinvent and Agrybalyse (Koch and Salou, 2022) databases were used. In addition, energy consumption and the amount of water used for feed formulation were obtained from Nemecek & Kagi, (2007). For the impact of electricity, data from the Ecoinvent database on the Italian national electricity mix were used. Finally, literature data from García et al. (2019) were used to model the impact of fingerling production.

3.4.2.4. Energy analysis

To characterize all inventory data in terms of their impact on CED, the cumulative energy demand based on the method published by Ecoinvent V1.01 and expanded by PRé for energy resources available in the SimaPro database was applied (Frischknecht et al., 2007). In particular, the fuels' higher heating values default version of CED was used. The characterization factors of this method are divided into 5 sub-categories: (I) Non-renewable, fossil (NR-f); (II) Non-renewable, nuclear (NR-n); (III) Non-renewable, biomass (NR-b); (IV) Renewable, biomass (R-b); (V) Renewable, water (R-wa); (VI) Renewable, wind, solar, geothermal (R-wsg).

3.4.2.5. Results interpretation and sensitivity analysis

Contribution analysis was carried out to identify the energy demand of the individual sub-processes. In particular, the following sub-processes were taken into consideration: i) electricity consumption; ii) fuel consumption; (III) feed production and supply; (IV) liquid oxygen production and supply; (V) juveniles production and supply; (VI) infrastructure and equipment production, maintenance and disposal;

A sensitivity analysis on energy sources was performed. In more details, for land-based farms, the current national electricity mix was replaced with the projected 2030 electricity mix, according to INECP, (2019) **(Table 2).** The Ecoinvent V3.9 database was used for modelling electricity derived from various sources.

Regarding coastal farms (CO1 and CO2), the consumption of traditional diesel has been completely replaced by the consumption of biofuel (B100), with a calorific value of 37.3 MJ/kg and a density of 890 kg/m³ (EMEP/EEA, 2023). To model the impact of biofuel production, the Ecoinvent process for the production of Fatty-Acid-Methyl-Ester (FAME) was considered.

Table 2: *Percentage distribution of the national electricity mix in 2030 according to the scenario reported by INECP (2019)*

Source	**% on total electricity mix**
Blast furnace gas	0.86
Oil and petroleum products	1.2
Natural gas	34.15
Renewables and biofuels	53.92
Hydro power	*14.6*
Wind power	*11.88*
Solar photovoltaic	*21.22*
Geothermal	*2.09*
Primary solid biofuels	*1.9*
Biogas	*1.71*
Renewable municipal waste	*0.51*
Non-renewable waste	0.51
Import net	8.46
CSP	0.89
Total	100

3.4.3. Results

Table 3 reports the results of the absolute impacts and the percentage of individual energy sources on the CED.

The absolute results show a significant range in CED. Specifically, in the two LB farms, the CED is 168,535 and 188,642 MJ/t, while it is lower in the two coastal farms, with values of 66,224 and 76,507 MJ/t for CO1 and CO2, respectively. The percentage difference between the CED of LB2 (worst environmental case) and CO1 (best environmental case) is 65%; the percentage difference between LB1 and LB2 is 11%, while CO2 has a CED 13% higher than CO1.

LB2 is therefore the farm with the highest CED, due to a higher electricity consumption per ton of fish produced. In all subcategories, it has the highest impacts, except for the NR-n category (16,402 MJ/t), where LB1 has the highest impact (37,624 MJ/t). Although with the second largest CED, LB1 has the lowest impact in the NR-b (34 MJ/t) and R-b (22,434 MJ/t) categories. CO1 and CO2, on the other hand, have the lowest cumulative impacts as well as in all other impact categories. Additionally, CO1 consistently has lower impacts than CO2.

The NR-f category represents about 50% of the CED in all analysed cases: specifically, it represents 53.4% and 59.7% of the CED in LB1 and LB2, and 57.4% and 47% in CO1 and CO2. In 3 out of the 4 cases, the second contributor to CED is R-b (20.5% in LB2, 33.8% in CO1, and 41.4% in CO2), while in LB1 the second contributor is NR-n (22.3% of the CED), followed by R-b (13.3%). Overall, the energy demand from non-renewable sources is greater than that from renewable sources: specifically, in LB1 and LB2, the non-renewable categories represent 75.7% and 68.5% of the CED, respectively, while in CO1 and CO2 they represent 56.3% and 43.7% of the CED, respectively.

Table 3: *Absolute results of the impacts calculated for each analysed farm and the percentage contribution to the cumulative energy demand of each category. Conditional formatting is to be read row by row and highlights in red the highest impacts, and in yellow and then green as impacts decrease. Legend: Non-renewable, fossil (NR-f); Non-renewable, nuclear (NR-n); Non-renewable, biomass (NR-b); Renewable, biomass (R-b); Renewable, wind, solar, geothermal (R-wsg); Renewable, water (R-wa). UF: 1 t of fish*

Category	**LB1**		**LB2**		**CO1**		**CO2**	
	Value (MJ)	**% on CED**	**Value (MJ)**	**% on CED**	**Value (MJ)**	**% on CED**	**Value (MJ)**	**% on CED**
Non-renewable, fossil	89,956	53.4	112,594	59.7	38,031	57.4	35,993	47.0
Non-renewable, nuclear	37,624	22.3	16,402	8.7	4,213	6.4	7,004	9.2
Non-renewable, biomass	34	0.02	257	0.1	67	0.1	99	0.1
Renewable, biomass	22,434	13.3	38,617	20.5	22,386	33.8	31,696	41.4
Renewable, water	8,334	6.0	9,432	6.0	330	1.8	582	1.5
Renewable, wind, solar, geotherm	10,153	4.9	11,340	5	1,198	0.5	1,134	0.8
CED	168,535		188,642		66,224		76,507	

Figure 2 shows the impact share related to each subprocess of the system for each category of energy source (as explained in section 2.5). The main difference between the two rearing systems is the use of electricity and liquid oxygen in land-based systems. These two factors, in the NR-f category, together represent 56,216 MJ out of 89,956 MJ total in LB1, while in LB2 they account for 78,625 MJ out of 112,594 MJ total. The feed, on the other hand, represents 30,359 and 30,304 MJ, which is similar to those found in CO1 and CO2, respectively, at 31,558 and 31,099 MJ. In the NR-b category, feed in LB2 farm has a much greater impact (241 MJ/t) compared to the other farms (25, 49, and 90 MJ/t for LB1, CO1, and CO2, respectively). Oxygen consumption is the main contributor for the NR-n demand in LB1, accounting for 31,006 MJ out of a total of 37,624 MJ/t; on the contrary, energy consumption in this category impacts more in LB2 (8,342 MJ) compared to LB1 (3,441 MJ/t). In this category as well, the impact due to feed in the different systems is similar and ranges from 2,712 MJ/t in LB1 to 6,545 MJ/t in CO2. The R-b category is almost entirely due to feed consumption in all the analysed farms: in LB1 and CO1, the impact is similar (19,666 and 21,971 MJ/t, respectively), while it is also similar but higher between LB2 and CO2 (36,221 MJ and 31,474 MJ/t, respectively).

Significant differences between the two types of farms are also reported in the R-wa and R-wsg categories, where CO1 and CO2 have much lower impacts compared to LB1 and LB2. In detail, in R-wa, the impact of CO1 and CO2 is almost entirely due to feed (957 and 997 MJ out of a total of 1,198 and 1,134 MJ/t, respectively), while in LB1 and LB2, besides feed (927 and 883 MJ/t), the impact is mainly due to oxygen consumption (5,611 and 1,999 MJ/t) and electricity consumption (3,478 and 8,433 MJ/t). A similar trend is observed in the R-wsg category, where feed is responsible for 157 and 477 MJ/t out of a total of 330 and 582 MJ/t in CO1 and CO2; in LB1, the impact is divided between electricity consumption (3,553 MJ/t) and oxygen (4,541 MJ/t), while in LB2, the impact of electricity is higher (8,615 MJ/t), but the impact of oxygen is lower (535 MJ/t).

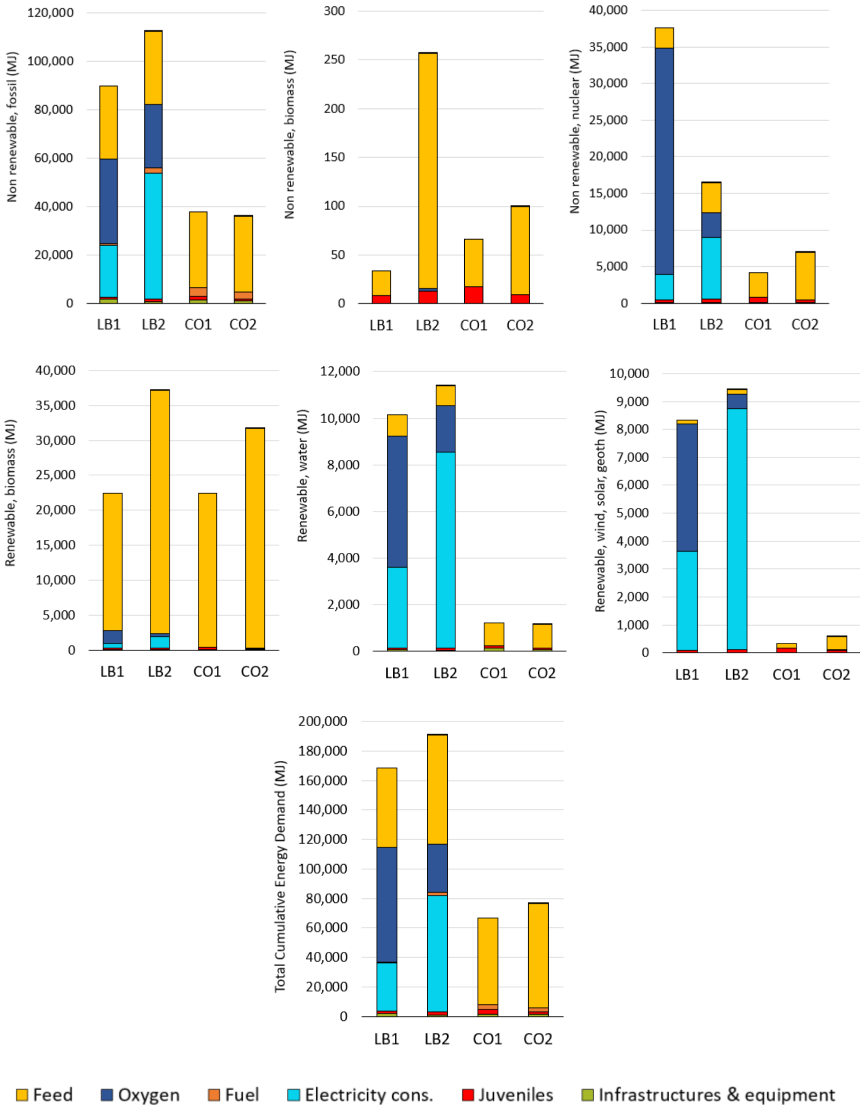

Figure 2: *Analysis of the contributions of absolute values for all analysed CED categories and the CED. UF: 1 t of fish*

Finally, in the characterization of CED, the feed has a similar impact in LB1 and CO1 (53,837 and 58,083 MJ/t, respectively) and is also similar but higher between LB2 and CO2 (71,784 and 70,682 MJ/t). It is also important to note that the total share of CED from the sum of electricity and oxygen is very similar between LB1 and LB2 (110,316 and 112,006 MJ/t), but in LB1, the predominant share is due to oxygen (77,665 MJ/t), while in LB2, it is due to electricity (79,163 MJ/t).

Lastly, other production factors (fuel, infrastructures and equipment, and juveniles) play a minor role in the definition on CED and other subcategories.

3.4.3.1. Sensitivity analysis implications

Table 4 shows the relative variations between the real case scenarios (RS) and the alternative scenarios (AS) in all sub-categories and in CED.

For LB1 and LB2, the main variation concerns the increase in the use of renewable energy from wind, solar, and geothermal sources, with an increase in this category of 34% in LB1 and 72% in LB2. Additionally, renewable energy from water sources also increases by 1% in LB1 and 2% in LB2. Conversely, and as expected, non-renewable sources decrease: NR-f decreases by 2% in LB1 and 5% in LB2, NR-n decreases by 3% in LB1 and 15% in LB2, while NR-b remains constant.

For CO1 and CO2, the use of biodiesel significantly increases the NR-b category (+126% in CO1 and +53% in CO2), accompanied by a decrease in NR-f by -6% in CO1 and -4% in CO2. R-b also increases by 11% in CO1 and 5% in CO2. Finally, the other categories have more contained variations, ranging between 1-2% in both farms.

Finally, the different sources of energy supply, and therefore the different infrastructures and supply chains that characterize them, change the impacts of the subcategories but have practically no effect on the CED of the farms, with contained variations always below 1%.

Table 4: *Percentage changes in the impact of the alternative scenario (AS) calculated relative to the real scenario (RS). AS refers to the calculation of the energy requirements using the assumptions outlined in section 2.5*

Category	**Δ % (AS-RS)/RS**			
	LB1	**LB2**	**CO1**	**CO2**
Non-renewable, fossil	-2%	-5%	-6%	-4%
Non-renewable, biomass	-3%	-15%	1%	0%
Non-renewable, nuclear	0%	0%	126%	53%
Renewable, biomass	-1%	-2%	11%	5%
Renewable, water	34%	72%	2%	1%
Renewable, wind, solar, geotherm	1%	2%	2%	1%
Cumulative Energy Demand	-0.3%	-0.6%	0.35%	0.19%

Regarding the characterization of CED, **Figure 3** shows the share of the energy from non-renewable and renewable sources in the two scenarios (RS and AS).

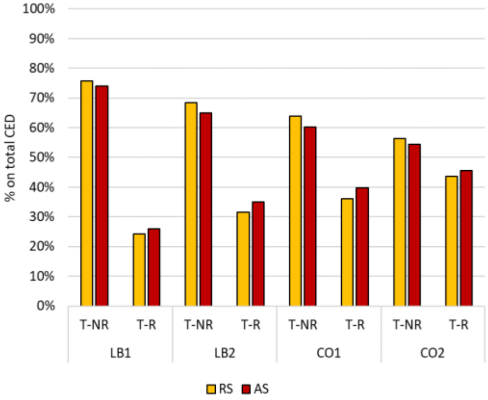

Figure 3: *Comparison of the percentages of total non-renewable energy (T-NR) and renewable energy (T-R) on the CED of the real scenario (RS) with the alternative scenario (AS)*

In all cases, in AS, renewable energy increases and is greater than in the RS, and consequently, non-renewable sources show an opposite trend. Specifically, in LB1, T-NR decreases from 76% to 74%, while T-R increases from 24% to 26%. In LB2, T-NR drops from 69% of the total to 65%, while T-R rises from 31% to 35%. The same trend is observed in coastal farms: in CO1, T-NR decreases from 64% to 60% of the total energy, while renewable energy increases from 36% to 40%. Finally, in CO2, T-NR decreases from 56% to 54%, while T-R increases from 44% to 46%. For further details on the absolute values of the various categories and their percentages of the total, refer to **table S5** in the supplementary materials.

3.4.4. Discussion

This study analysed and characterized the CED of different aquaculture farms across different sub-categories. As expected, land-based farms showed a higher CED compared to coastal farms. According to our knowledge, no study so far has specifically focused on the CED of ESB and GSB production in the Mediterranean, although there are reviews on energy use in aquaculture and some LCA studies on those species that also report this impact category. In more detail, the results of this study are in line with those of other LCA studies focusing on ESB and GSB production. In particular, Abdou et al. (2017) report a CED of 57,198 and 51,098 MJ/t for ESB and GSB, respectively, farmed in a coastal sea-cage farm. Two other LCA studies (Abdou et al., 2018 and Garcia et al., 2016) reported CED values of ESB and GSB production: Abdou et al., (2018) reported a CED ranging from 44,000 to 59,000 MJ/t, while Garcia et al., (2016) reported a higher value (98,120 MJ/t). The only LCA study in the literature focused on land-based farm is Jerbi et al. (2012): they reported a much higher CED than the previous studies, due to the high energy consumption required, with values of 280,000 MJ/t and 175,000 MJ/t, which are, in any case, in the same order of magnitude as LB1 and LB2 of this study **(figure 4).** The energy demand for land-based systems can be highly variable. With an energy demand of 9.5 and 5.3 kWh/kg of fish, respectively, the LB1 and LB2 farms in this study rank low compared to RAS systems (3-81.46 kWh/kg of fish, Ayuso Virgili et al., (2023)), but have a higher energy demand when compared to other Flow Through Systems (FTS), where Samuel Fitwi et al., (2013) reports an energy demand of 2.55 kWh/kg of fish.

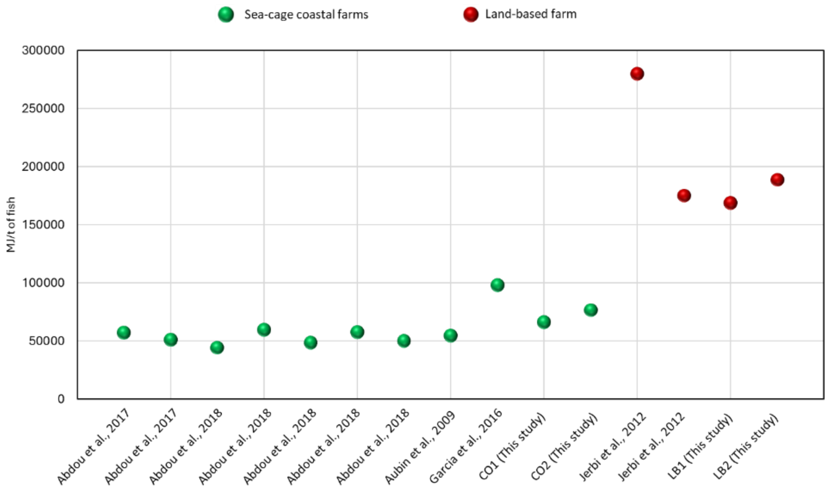

Figure 4: *Comparison of CED values with values reported in LCA literature papers for Seabass and Seabream. Coastal farms are highlighted in green and land-based farms are highlighted in red.*

More generally, Pelletier et al., (2011) analysed the energy intensity of agriculture and food systems, including aquaculture; they reported an energy demand for aquaculture systems ranging from 20,000 MJ/t (for farmed Tilapia) to 50,000 MJ/t (for farmed ESB) of product. Additionally, the average energy demand for fisheries was reported to be about 35,000 MJ/t of fish. However, these latter results concerning fishing activities are highly variable due to the great diversity between, for example, artisanal fleets dependent on wind, tides and manual labour to highly industrialised vessels equipped with advanced technologies that characterise the sector. According to Troell et al. (2004) energy inputs could be divided into direct and indirect (or embodied) energy: direct energy inputs to aquaculture operations encompass a range of activities, including the collection/production of juveniles, general system operations, and the harvesting; indirect (or embodied) energy is represented by fixed capital inputs such as different forms of enclosures (tanks, nets, etc.), feeders, aerators, pumps, boats, vehicles, etc. As reported by Tyedemers, (2004), unlike other food production sectors, direct inputs account for the preponderant share (75-90%) of energy demand in industrial fishing activities. In aquaculture systems, the ratio between direct and indirect energy can vary greatly depending on the type of system. While open systems rely on ecosystem services to maintain water quality and, in some cases, natural productivity, closed systems must be supplemented with increasing levels of material and energy inputs (Pelletier et al., 2011). Intensive land-based flow or recirculating systems are often characterised by significant energy input for activities such as pumping and filtering water (Badiola et al., 2018). In land-based systems, the direct consumption of electricity for water supply and pumping, and the operation of aerators represents a significant share of the CED. For example, in LB1 and LB2 of this study, the direct electricity consumption represents 19% and 42% of the CED, respectively. In coastal farms, on the other hand, the direct energy consumption is much lower, as it is mainly represented by the fuel consumption for navigation to reach the sea-cages, while the predominant share of energy is due to the use of aquafeeds. For instance, in CO1 and CO2 of this study, the share of CED linked to fuel consumption is 5%, while that linked to feed reaches up to 90%. The same trend can also be found in Abdou et al. (2017) where feed represented 72% and 79% of the total, while fuel consumption accounted for 8% and 7% of the CED. This is also confirmed in other species: for example, Pelletier et al., (2009) reported that aquafeed is responsible for over 90% of the CED in globally produced Atlantic salmon farming. Therefore, feed composition also plays a key role in determining the CED of aquaculture systems, as very different energy requirements can be incorporated into different feed sources (Henriksson et al., 2013). In addition, the low share related to fuel is certainly due to excellent farm management and the large scale of the farm, where the fuel is distributed over a large quantity of farmed fish. The fuel intensity of CO1 and CO2 is indeed 68 and 83 l/t of fish, respectively. Parker et al. (2018) reported a global average fuel intensity of 489 l/t of fish for fisheries, which also explains the difference between direct and indirect energy in fishing and aquaculture.

The use of energy from fossil and non-renewable sources has already peaked, and several forecasts indicate that the use of renewable sources is set to grow significantly, potentially covering 30-80% of energy needs by 2100 (Monforti-ferraio et al., 2015). Currently, hydropower and traditional biomass account for a significant part of the global energy mix, contributing about 18% of global energy consumption. On the other hand, new renewable sources, such as solar, wind and geothermal energy, account for only about 2% of global primary energy consumption. Solar energy for electricity production, in particular, is not yet commercially competitive in many areas, while biomass, wind and geothermal energy are making relatively rapid progress (Badiola et al., 2018). In this context, in order to address problems such as global warming, it will be crucial to integrate local energy sources into national or regional systems, using the most appropriate energy, whether local or imported (Fridleifsson, 2001). Therefore, it is important for industry to support energy savings at the farm level (Rosen and Dincer, 2001) and the replacement of fossil fuels with renewable sources (Aubin et al., 2009).

A sensitivity analysis on energy sources was conducted in this study. The scenarios created in this study allow for an increase in the share of renewable energy used in the farms analysed: note that these are hypothetical scenarios, no modifications to the plants and farms have been considered and results in reality may vary. In any case, increasing renewable sources, as already highlighted in other studies (Badiola et al., 2018) can also decrease the environmental impact in terms of climate change of the aquaculture sector. In this study, the electricity of the alternative scenario has an environmental impact on climate change, per kWh, that is 15% lower than the current Italian national electricity mix (0.322 kg CO2 eq/kWh for the former, 0.382 kg CO2 eq/kWh for the latter), while the use and combustion of biodiesel has an impact on climate change of 11% less than a conventional diesel (0.083 kg CO2 eq/MJ for the former, 0.094 kg CO2 eq/MJ for the latter). Finally, it is important to remark that alternative scenarios are simulations based on assumptions and average values from the literature, therefore, the reality may differ; in particular, for land-based farms the difference may be very marked depending on the country as energy sources are very site-specific, creating diverse environmental impacts and depend on different energy sources and in different proportions.

3.4.5. Conclusions

This study provides a detailed analysis of the CED associated with ESB and GSB production in different aquaculture systems in the Mediterranean region. By comparing land-based farms and coastal sea-cage farms, the research highlights significant differences in energy consumption patterns and identifies key areas where energy efficiency improvements can be made. The results demonstrate that land-based farms have a significantly higher CED compared to coastal farms, primarily due to the extensive use of electricity for water circulation, aeration, and temperature control. In contrast, coastal farms, while less energy-intensive, still exhibit substantial energy demands, particularly from the production and use of aquafeeds. These findings align with previous studies, confirming that the type of farming system plays a critical role in determining the overall energy footprint of aquaculture operations. Sensitivity analysis also suggests that projecting land-based farms to 2030 could reduce their reliance on non-renewable energy sources and potentially reduce their environmental impact. However, the actual implementation of such strategies would require site-specific considerations and may vary depending on local energy infrastructure and availability. In conclusion, this study underscores the importance of energy management in aquaculture and the need for targeted strategies to reduce energy consumption in both land-based and coastal farming systems. As the global demand for seafood continues to rise, optimizing energy use in aquaculture will be essential for ensuring the sustainability and economic viability of this growing industry. Future research should focus on the development of energy-efficient technologies and practices, as well as the exploration of renewable energy integration in diverse aquaculture settings.

3.4.6. References

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SUPPLEMENTARY MATERIALS

Table S1: *Percentage composition of the ingredients of the different feeds fed in the farm LB1*

Ingredients, %	**Feeds**		
	Feed 1	**Feed 2**	**Feed 3**
Fish meal	30	35	35
Sunflower meal		25	
Wheat gluten meal	25		
Fish oil	15	14	14
Rapeseed meal		15	25
Soybean meal	15		12
Maize flour	14	10	13
Sodium chloride	0.75	0.75	0.75
Monoammonium phosphate	0.25	0.25	0.25
Annual distributed quantity (t)	55.4	38.7	1097
	Common input		
Electricity	35 kWh/t of feed		
Heat from natural gas	145 MJ/t of feed		
Tap water	56 kg/t of feed		

Table S2: *Percentage composition of the ingredients of the different feeds fed in the farm LB2*

Ingredients, %	**Feeds**			
	Feed 1	**Feed 2**	**Feed 3**	**Feed 4**
Fish meal	29	20	21	21
Wheat flour	16.1	13.6	15	14
Corn gluten meal	13.8	15.4	17	21
Soybean protein concentrate	12.3	14	8	14
Soybean meal	11.7	15		
Guar meal			16	14
Fish oil	11.1	12	14	14
Rapeseed meal	4.5	5	4	
Sunflower meal		4	3	
Whey	1.5	1	2	2
Annual distributed quantity (t)	32	297.4	560.42	240.18
Common input				
Electricity	35 kWh/t of feed			
Heat from natural gas	145 MJ/t of feed			
Tap water	56 kg/t of feed			

Table S3: *Percentage composition of the ingredients of the different feeds fed in the farm CO1*

Ingredients, %	**Feeds**							
	Feed 1	**Feed 2**	**Feed 3**	**Feed 4**	**Feed 5**	**Feed 6**	**Feed 7**	**Feed 8**
Fish meal	35	25	9	9	8.5	9	10.5	7
Corn gluten meal	15	20	24	27	24	27	24	27
Rapeseed meal			23	23	22	23	24	25
Wheat gluten meal	12	16						
Wheat middlings	12	13	13.2	12.3	12	12.3	10.5	11
Soybean meal	11	11						
Guar meal			10	11	9.8	11	10.5	10
Fish oil	9	90	8.2	6.5	10.5	6.5	6.7	6.5
Canola oil			5.8					
Rapeseed oil				5.2	6.6	5.2	6.8	5.5
Bacteria protein meal			5.8	5	5.6	5	6	7
Krill meal	5	5						
Sodium chloride	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Monoammonium phosphate	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Annual distributed quantity (t)	70	140	140	140	800	800	900	900
Common input								
Electricity	35 kWh/t of feed							
Heat from natural gas	145 MJ/t of feed							
Tap water	56 kg/t of feed							

Table S4: *Percentage composition of the ingredients of the different feeds fed in the farm CO2*

Ingredients, %	**Feeds**		
	Feed 1	**Feed 2**	**Feed 3**
Fish meal	30	35	35
Sunflower meal		25	
Wheat gluten meal	25		
Fish oil	15	14	14

Rapeseed meal		15	25
Soybean meal	15		12
Maize flour	14	10	13
Sodium chloride	0.75	0.75	0.75
Monoammonium phosphate	0.25	0.25	0.25
Annual distributed quantity (t)	448	929	2129
Common input			
Electricity	35 kWh/t of feed		
Heat from natural gas	145 MJ/t of feed		
Tap water	56 kg/t of feed		

Table S5: *Alternative scenarios (AS) results. Absolute results of the impacts calculated for each analysed farm and the percentage contribution to the cumulative energy demand of each category with alternative energy sources. UF: 1 t of fish.*

Category	**LB1 (AS)**		**LB2 (AS)**		**CO1 (AS)**		**CO2 (AS)**	
	Value (MJ)	**% on CED**	**Value (MJ)**	**% on CED**	**Value (MJ)**	**% on CED**	**Value (MJ)**	**% on CED**
Non-renewable, fossil	87837	52.3	107456	57.3	35569	53.5	34466	45.0
Non-renewable, nuclear	36635	21.8	14006	7.5	4248	6.4	7026	9.2
Non-renewable, biomass	34	0.02	257	0.14	151	0.23	151	0.20
Renewable, biomass	22143	13.2	37912	20.2	24935	37.5	33280	43.4
Renewable, water	11152	6.6	16264	8.7	336	0.5	585	0.8
Renewable, wind, solar, geotherm	10233	6.1	11532	6.2	1219	1.8	1147	1.5
CED	168033	100%	187426	100%	66458	100%	76655	100%

CHAPTER 4 - Evaluation of two possible strategies to mitigate the environmental impact of aquaculture

4.1. Scientific article 5: Upscaling and environmental impact assessment of an innovative integrated multi-trophic aquaponic system

Published in: *Journal of Environmental Management,* 369 (2024) 122327

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After exploring the current state in Chapter 3, this paper evaluates the environmental performance of an innovative integrated multi-trophic aquaponic system. This represents an innovative system consisting of a fish section (where sea bass and sea bream were farmed), a section of detritivore filter-feeding organisms (such as mussels, clams, and polychaetes), and a hydroponic section where Salicornia was cultivated. The underlying concept is to couple the production of different species and trophic levels to assess whether the production of an integrated system can provide environmental benefits compared to traditional aquaculture farms. Two scenarios were evaluated, including one where the fish were fed with commercial feed and another where an alternative semi-self-produced feed was used within the system itself. Given the low Technology Readiness Level (TRL) of this plant, an ex-ante LCA methodology was applied. Due to the incomplete self-sufficiency of production, the supply of alternative feed resulted in a greater impact compared to the scenario with traditional feed, except in the impact category of eutrophication, which benefited from the nutrient absorption of the detritivore filter organisms.

4.2. Scientific article 6: Insights into different marine aquaculture infrastructures from a life cycle perspective

Published in: *Aquacultural Engineering*, 107 (2024) 102462

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Since infrastructures have emerged as elements that are rarely analyzed from an environmental impact perspective, the second mitigation strategy examined was the replacement of traditional nylon nets in sea cages with innovative nets made of copper alloy. This paper specifically addresses how the environmental impact of sea bass and sea bream production in coastal farms would change by using new copper nets instead of traditional nylon nets in the coastal cages. Therefore, the aim of this study is to evaluate the potential benefits and challenges associated with integrating copper nets into existing aquaculture systems. The analysis showed that while the use of copper cages certainly extends the service life of marine aquaculture infrastructure, it is environmentally more sustainable only when full recyclability of the copper net is achieved.

CHAPTER 5 - Application of a multi-criteria model (DEXiAqua) to assess the overall sustainability of aquaculture systems

5.1. Introduction

Nowadays, aquaculture systems are asked to be more sustainable to better manage financial, technological, institutional, natural, and social resources (Le Feon et al., 2021). The growing world population, projected to reach 9 billion by 2050, drives the demand for seafood, with per capita consumption increasing significantly (FAO, 2018). However, aquaculture has various direct impacts, such as the emission of fish farm effluents (nitrogen, phosphorus, etc.) and potential effects on endemic species from introducing non-native species or propagating diseases, alongside indirect impacts related to fish feed production. Consequently, aquaculture needs to mutate to pursue its growth sustainably.

Sustainability assessment of food systems necessitates merging multiple criteria and disciplines. The objective is to develop systems that reduce environmental impacts while being economically viable and socially fair. Evaluating environmental, social, and economic impacts together is crucial, as these dimensions are interconnected and collectively influence the overall sustainability of aquaculture practices. This holistic approach considers the complex interactions among various factors, such as resource use, economic viability, and social equity, thereby ensuring a comprehensive understanding of sustainability (Rey-Valette et al., 2008). The participation of diverse stakeholders is essential in this process to incorporate multiple perspectives and values.

In this context, multi-criteria decision analysis (MCDA) methods provide a relevant framework. MCDA explicitly considers multiple criteria, aiding individuals or groups in exploring important decisions (Belton & Stewart, 2012). It integrates objective measurements with value judgments, using both quantitative and qualitative indicators, and manages subjectivity through organized stakeholder engagement. An important advantage of MCDA is its ability to manage diverse and sometimes conflicting goals inherent in sustainability evaluation, such as balancing profitability with environmental stewardship (Sadok et al., 2009). MCDA methods, particularly those integrated into decision support systems (DSS) like DEXi, offer the ability to analyze qualitative factors—such as social and cultural impacts—alongside quantitative ones (Bohanec et al., 2007).

There are several MCDA methods that could be used (Sadok et al., 2008): Multi-Attribute Utility Theory (MAUT) and Analytic Hierarchy Process (AHP) are prominent in MCDA applications and are effective for decision-making involving well-defined quantitative criteria. However, they rely heavily on compensatory aggregation, where poor performance in one criterion can be fully offset by strong performance in another. For instance, while AHP allows for pairwise comparisons of criteria, its reliance on subjective judgments and quantitative data limits its applicability when qualitative or mixed data are integral to the assessment. Outranking methods like ELECTRE and PROMETHEE are widely used for ranking alternatives, especially when managing conflicts between criteria. These methods are advantageous for their ability to handle incommensurability and partial compensation among criteria, making them suitable for many agricultural and environmental contexts; however, their inability to explicitly manage mixed qualitative and quantitative data or incorporate decision-making rules limits their effectiveness in holistic sustainability assessments. Mixed methods, such as decision rule-based approaches, offer significant advantages for handling qualitative and quantitative data simultaneously. These methods rely on "if-then" rules derived from expert knowledge and are particularly suited for sustainability assessments involving complex and non-compensatory relationships among criteria. However, they can become cumbersome in situations requiring numerous rules to represent complex decision problems. For these reasons, DEXi methods (Bohanec, 2011) were selected as the MCDA framework in this study. DEXi has been successfully applied in the agricultural sector to develop sustainable assessment tools and synthesize expert knowledge in various contexts, including cropping systems (Sadok et al., 2009), organic production (Colomb et al., 2012), and soil quality (Bohanec et al., 2008). The MASC (Sadok et al., 2009) model, for example, demonstrated the capability of DEXi-based methods in handling the environmental, economic, and social dimensions of sustainability in a single comprehensive framework by combining quantitative and qualitative information into meaningful sustainability scores. Its rule-based approach allows for the integration of qualitative and quantitative data without requiring full compensatory aggregation, preserving the complexity of trade-offs in sustainability evaluations. Moreover, DEXi structure enables the incorporation of expert knowledge into decision rules, ensuring that the analysis reflects the nuanced realities of the systems. By supporting both numerical indicators and categorical judgments, DEXi can facilitates a comprehensive assessment of environmental, economic, and social dimensions, addressing the specific challenges posed by aquaculture sustainability. This flexibility and robustness make it particularly well-suited for the multidimensional nature of this study, ensuring a more balanced and transparent evaluation compared to the alternatives.

Similarly, DEXiAqua is a tool developed within the SIMTAP project, specifically tailored for aquaculture systems (Le Feon et al., 2021). This method incorporates environmental, social, and economic dimensions into a comprehensive sustainability assessment, ensuring that the interplay among these aspects is effectively analysed. A key feature of DEXiAqua is the integration of Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (Social LCA). These methods allow for a detailed examination of environmental impacts, cost-effectiveness, and social implications, respectively, offering a balanced and multidimensional approach to sustainability. The DEXiAqua model builds on the strengths of previous DEXi applications, such as its use in cropping systems (Sadok et al., 2009), by allowing complex decision rules to integrate qualitative knowledge about ecological impacts and economic factors. While Le Feon et al. (2021) discusses the methodology development and its application to a Norwegian salmon farm, no application has been performed to the farming of Sea bass and Sea bream.

Therefore, this section of the thesis aims to evaluate the overall sustainability of a land-based farm specialized in the production of these species, integrating environmental, economic, and social aspects. To this purpose, the DEXiAqua methodology has been briefly introduced, a data collection regarding environmental, social, and economic information has been conducted in a land-based farm, and the analysis along with its results are presented.

5.2. Material and methods

The methodological elements presented here are extracted from a peer reviewed paper derived from the SIMTAP project (Le Feon et al., 2021) and from the deliverable “General report on multicriteria performances of SIMTAP in different contexts” of the SIMTAP project.

Following the DEX method different steps were followed. The main steps were to (i) build a conceptual model based on indicators to describe the three pillars of sustainability in aquaculture system, based on technical and scientific literature, (ii) determine ponderation factors for the aggregation of the different attributes, (iii) determine thresholds to convert quantitative and/or qualitative values into scales (as for example low/medium/high). A template for data collection has been developed in order to collect the raw necessary data, and calculate first level of indicators. This template could be used furthermore by fish producer or policy decision makers.

5.2.1 DEX method and DEXi software

DEXi is a software that enables to simplify complex systems in order to be able to take multi-attribute decisions (Estorgues et al., 2017). It is especially designed to choose between different options, scenarios or systems, by taking into account numerous parameters (Bohanec, 2008).

It decomposes a multi-factorial problem into smaller sub-problems and so on, until obtaining several problems easier to solve (Figure 5.1). DEXi can then be used both to evaluate different scenarios or options for a multi-factorial system and help decisions. Different steps are necessary to define a DEXi model (Bergez, 2013):

- Define attributes: each sub-problem is represented by a qualitative variable, called an attribute. An attribute correspond to each node of the tree;
- Define scales: for each attribute, sets of classes are defined as for example [“Low”; ”Medium”; ”High”] or [“Acceptable”; “Unacceptable”];
- Define the tree of attributes: This tree illustrates the breakdown of the main problem into sub-problems (branches);
- Define utility functions: utility functions enable the aggregation of the branches from the bottom of the tree (sub-problems) to the top (the overall problem being evaluated). For example, it can be expressed as: “IF sub-problem #11 is Low and sub-problem #12 is High, THEN problem #1 is Medium.”

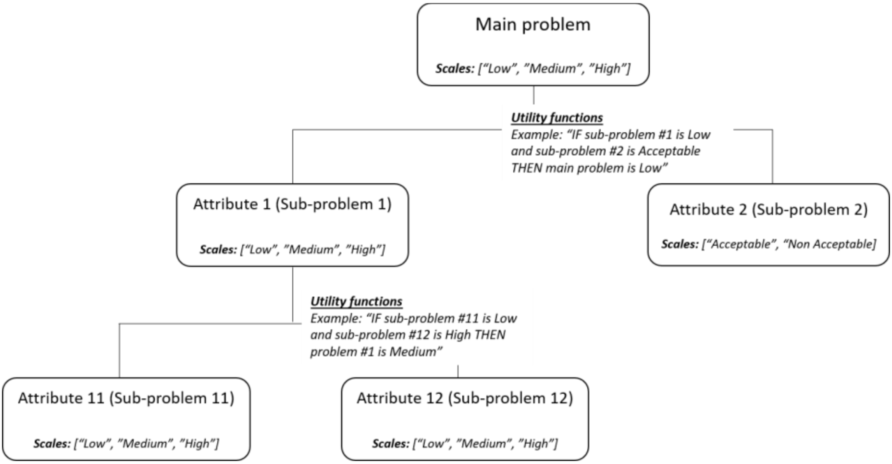


Figure 5.1: *Description of DEXi principles and lexical field. Figure retrieved by Le Feon et al., (2021)*

DEXi uses a combination of qualitative and quantitative attributes, which are aggregated and weighted to produce a final sustainability score. This approach allows the integration of both numerical data and subjective considerations, such as social factors. Once the DEXi model is established, scales are assigned to each attribute. For qualitative attributes, the user selects from predefined options, each associated with a specific scale. For quantitative indicators, thresholds are defined, and when the user inputs a value, the corresponding scale is automatically assigned. The software compiles utility functions to evaluate the scenario, providing a qualitative result (e.g., "this scenario is good"). Sub-evaluations further highlight areas that need improvement, allowing users to break down the evaluation and pinpoint specific attributes requiring attention. This approach helps improve the overall sustainability score and enables comparisons across multiple scenarios using the same DEXi model, allowing for ranking based on trade-offs and sub-problems.

The DEXiAqua framework integrates several well-established methodologies, such as Life Cycle Assessment (LCA), Emergy Accounting, Social Life Cycle Assessment (SLCA), and Life Cycle Costing (LCC), offering a comprehensive evaluation of sustainability from various dimensions:

Life Cycle Assessment (LCA) is used to quantify some environmental impacts. In DEXiAqua, LCA focuses on seven key impact categories essential for evaluating the environmental effects of aquaculture systems: Eutrophication potential (EP) in kg PO_4^{3-} equivalents, Acidification potential (AP) in kg SO_2 equivalents, Global warming potential in kg CO_2 equivalents, Land competition in m^2a equivalents, Cumulative Energy Demand (CED) in MJ, and Net Primary Production Use (NPPU) in kg C. These categories help assess critical issues like nutrient pollution, climate change impact, land use, and energy consumption, providing a broad view of the environmental footprint of aquaculture practices. However, there are other environmental indicators calculated on the basis of the collected data, including, for example, On farm energy efficiency, suspended solid emissions, production loss, etc.

Emergy Accounting is a top-down quantitative approach that converts non-monetary (e.g., solar, wind) and monetary flows into their solar energy equivalents, expressed in Solar Emjoules (SEJ). In this study, two key emergy indicators were incorporated into the DEXi model: (1) The Emergy Yield Ratio, which reflects the system's ability to use local natural resources effectively, and (2) The percentage of renewability (%R), which indicates the extent to which the system relies on renewable resources. These indicators provide a deeper understanding of resource efficiency and sustainability within the broader environmental context.

Life Cycle Costing (LCC) assesses the economic sustainability of a product, process, or service over time by focusing primarily on costs. Although LCC predates LCA, it lacks standardized guidelines for implementation. Some general codes of practice have been proposed (Swarr et al., 2011), but different conceptual frameworks exist. In the literature, conventional LCC based on private cash flow models is the most common approach. For the DEXiAqua model, this conventional approach was adopted, offering a straightforward means to evaluate the long-term economic viability of aquaculture operations by considering both operational and capital expenses.

Social Life Cycle Assessment (SLCA) is similar to LCA but focuses on social impacts. It combines both quantitative and qualitative data to identify, evaluate, and manage the social consequences—positive or negative—that affect stakeholders throughout the life cycle of a product or service. The UNEP/SETAC guidelines (Sala et al., 2015) offer a framework for standardizing social impact assessments by identifying relevant stakeholders and defining indicators to measure social attributes such as working conditions, community engagement, and equity. In DEXiAqua, a Type I SLCA was implemented, where scores are assigned to social indicators based on thresholds or performance reference points, followed by weighting to reflect their importance. However, as these guidelines are broad and generic, they were adapted and refined for application to specific sectors like agriculture, fisheries, and aquaculture. The adaptation process involved an extensive literature review that identified key social attributes relevant to aquaculture, allowing the DEXiAqua model to address sector-specific issues such as worker well-being, social equity, and community impacts in a more accurate and context-sensitive way.

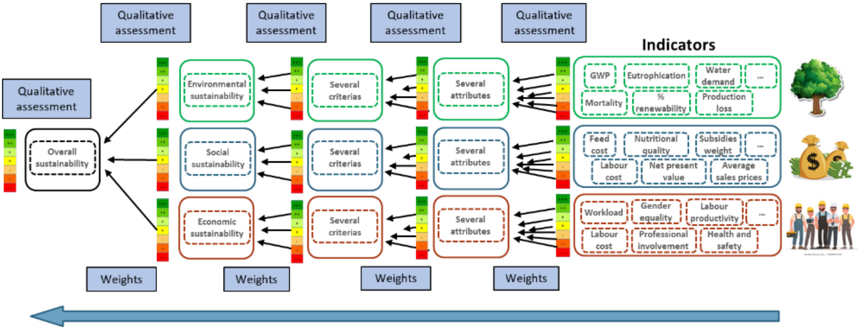


Figure 5.2: *Schematic representation of the DEXiAqua model structure. The indicators (on the left) receive a qualitative score and are aggregated, according to their weights, into different attributes and criteria, which are also analysed qualitatively. Finally, the aggregation results in a qualitative score for the three branches of sustainability (environmental, economic, and social), and by further aggregating them, an overall sustainability score is obtained*

5.2.2 Data collection and attributes calculation template

Data were collected through face-to-face interviews with the farmer and farm manager. A model was used to collect all the information needed to populate the DEXiAqua decision tree, including the data needed for life cycle assessment (LCA) (such as Emergy calculations), life cycle costing (LCC) and social life cycle assessment (SLCA). The model also allows for additional calculations to directly convert some data into relevant indicators. The model also allows for additional calculations to directly convert some input data into relevant indicators. Furthermore, the model integrates the process of determining the scales for each DEXi attribute by cross-referencing the data with the defined thresholds. Finally, the model produces a list of formatted scales, ready to be imported into the DEXi software to fit the developed model.

Although the model includes calculations for attributes, it is not completely independent. In particular, LCA and Emergy indicators are calculated with external tools based on the data collected. The results are then fed back into the model to determine the appropriate DEXi scales. The template is attached to this thesis (annex 1), while the result of the data collection, the implementation of some indicators and the comparison of these with the thresholds are shown in Table 5.1.

***Table 5.1**: Attribute values of the case study*

Indicators	**Unit**	**Value**	**Scale**
On farm energy efficiency	MWh/Ton	11.25	Very Low
Total feed conversion rate	kg/kg	2.51	Very High
Labour productivity	#	0.4	Very Low
Production loss	%	20.2	Medium
Nutritional quality	g [EPA + DHA]/100g	0.9	High
Average sales prices	€/kg	8.15	Very High
Paid labour costs	€/kg	1.4	Very High
Feed costs	€/kg	3.3	Very High
Juveniles and seedling costs	€/kg	0.7	Low
Net Present Value	€	0	Low
Internal Rate of Return	€	-38%	Low
Subsidies weight	€/kg	0	Low
Emergy Yield Ratio	#	1.12	Medium
Production diversification	#	2	Medium
Biosecurity and good practices	#	3	Medium
Resistance to environmental constraints	#	8	High
Specialization rate	%	60.29	Medium
Independence towards suppliers	#	0	Low
Independence towards customers	%	93.09	Low
Fish in Fish out Ratio	#	7.6	Very High

Interactions with professional institutions	NU	Option 3	High
Professional involvement	#	1	Medium
Workload	h/FTE/year	1,855.6	Medium
Health and safety	# days lost / 1000 hours	0.09	High
Job difficulty appreciation	NU	Option 2	Medium
Labour remuneration	NU	2.21	High
Working status	%	100	High
Education level	%	27.78	Medium
Gender equality	NU	Option 3	Low
Employment of worker with handicap	NU	Yes	Yes
Fish physical damages	%	1.8%	Low
Stocking density	kg/m^3	18	Low
Assured supply of food products	ton of dry Matter/FTE	8.4	Medium
Accessibility of products	#	6.36	Low
Contribution to employment	FTE/100000€	0.48	Low
Feedstuff locally produced	%	0	Low
Education contribution	NU	Option 2	Medium
Health costs	€/kg	0	Low
Total Nitrogen emissions	kg/ton	162.7	High
Suspended solid emissions	kg/ton	743.7	High
On farm ground surface used	m^2/ton	310.7	High
Global warming potential	ton CO_2 eq./ ton	6520	High
Acidification potential	kg SO_2 eq. / ton	37.1	High
Eutrophication potential	kg PO_4^{3-} eq/ton	118.23	High
Percentage of renewability	%	6.18	Low
Percentage of wild juveniles and plants used	%	0	Low
Water demand	m^3/kg	59.4	Medium
Net primary production use	t C eq/t	13.0	Low
Global land competition	m^2/ton	3,069	High
Total cumulative energy demand	GJ/ton	161.5	Very High
Percentage of nitrogen derived from co-products	%	0	Low
Percentage of phosphorus recovered	%	0	Low

Percentage of renewable energy used	%	60	High
Nitrogen use efficiency	%	15.07	Medium
Predator control	NU	Option 2	Acceptable
Multi-trophic integration	#	1	Low
Escapees management	%	0	Low

5.2.3 The analysed farm

The DEXiAqua model was applied to the Italian land-based farm from which economic and social as well as environmental data could be collected. The description of the farm can be taken from Zoli et al., (2023), as well as from the studies in Chapters 3.3 and 3.4.

Briefly, it is a land-based farm specialising in the production of Sea bass and Sea bream. The farm is located in Tuscany (Italy) and consists of several ponds of various sizes with a total area of about 150,000 m^2 . The production cycle starts with the sowing of fry weighing an average of 3 g, which are reared in specific ponds. Once the optimal size is reached, they are moved to the other ponds where they are reared up to a variable size (400 to 600 g). The total annual production is about 450 tonnes of fish. The feed conversion ratio (FCR = kg feed distributed/kg weight of live fish produced) is 2.4. The entire production process can be divided into several subsystems: (I) production, maintenance and disposal of infrastructure (pumps, tanks, predator nets, aerators and other equipment); (II) production and supply of fry; (III) production and supply of feed;

5.3. DEXiAqua results

Figure 5.3 is a radar chart that visually represents the scores of various sustainability criteria in the multicriteria assessment. It represents the penultimate level of aggregation with the relative scores. Each axis on the chart corresponds to a different sustainability criteria, with the scores ranging from 1 (score “low”) to 5 (score “very high”).

Environmental Sustainability (2/5)

Reduce Impact on Ecosystems (Rid. impact on ecos): This criteria scores 2/5, indicating a low level of sustainability in terms of minimizing environmental damage, particularly to local ecosystems. This result likely depends on indicators such as Total Nitrogen Emissions (low), Contribution to Eutrophication (low), and Global Warming Potential (low), which directly measure how the system impacts the environment.

Respect Natural Resources: Scoring 2/5, this criteria reflects a low sustainability score for resource use, which include indicators like Water Demand (score 2/4), Fish In Fish Out Ratio (score 1/5), and Land Competition (2/5). These are measurable indicators that reflect the system's efficiency in managing critical resources like water, feed, and land.

Ecological Efficiency (Ecological eff): With a 2/5 score, this criteria shows a low performance in ecological efficiency. This score depends mainly on indicators such as Feed Efficiency (score 1/5) and Nitrogen Use Efficiency (score 2/3).

Biodiversity (Biodiv): This criteria scores 3/5, indicating that the system performs moderately well in enhancing or maintaining biodiversity. Specific indicators that influence this score include Escapees Management (3/3), Production diversification (2/3) and Disease Management (2/3). These indicators directly measure the system's impact on local fauna and flora, as well as how well it prevents harm to wild populations.

Thus, the environmental score of 2/5 indicates that the system has significant environmental impacts, particularly in areas related to nutrient emissions, energy use, and ecosystem degradation.

Economic Sustainability (3/5)

The Economic Sustainability dimension evaluates the system's financial viability, and the production efficiency. A score of 3/5 indicates medium economic sustainability, with a balance between cost efficiency and market performance.

Production Efficiency (Prod eff): the system scores 3/5 in production efficiency, indicating a medium level of efficiency in converting inputs into outputs. This would likely be influenced by indicators such as Feed Conversion Ratio (score 1/5), On farm energy efficiency (score 2/5), and Labour Productivity (score 1/5). However, the average sales prices has an hight score (5/5) as well as the Juveniles costs (4/5).

Viability: score 3/5. This score depends on indicators such as Net Present Value /score 1/3), Internal Rate of Return (score 1/3), Subsidies Dependency (score 3/3) and specialization rate (score 3/3).This score reflects a system that is economically viable but could benefit from improved cost management and profitability strategies.

Social Sustainability (3/5)

The Social Sustainability dimension evaluates the system’s contribution to employment, working conditions, and relationships with other stakeholders. The score of 3/5 reflects a medium level of social sustainability, with some positive aspects and areas that require improvement:

Actors Relationships (Actors rel): With a lower score (2/5), this criteria reflects the system’s relationships with stakeholders, such as suppliers and customers. Indicators influencing this include Independence Towards Suppliers and Customers (score 1/3 for both), which measure how reliant the system is on external parties for operations, making it vulnerable to market changes. However, the indicator “Interaction with professional institutions scores high (3/3).

Employment and Working Conditions (Working cond): Scoring 3/5, this criteria measures the treatment and safety of employees. Indicators such as Health and Safety (score 1/3), Job difficulty appreciation (score 2/3), and Labour Remuneration (3/3) contribute to this score.

Meeting societal expectations (Soc expect): Scoring 3/5, this criteria reflects how well the system meets societal expectations, depending on indicators like Accessibility of Products (score 2/5), Nutritional Quality (score 1/5), and Animal Welfare (score 4/5). These indicators measure whether the system is providing socially beneficial outputs, such as high-quality and accessible food.

Contribution to the local development (Local dev): With a score of 2/5, this criteria reflects the system’s impact on local economic and community development. The measurable indicators contributing to this score include Contribution to employment (score 2/5), Education contribution (score 2/3), and feedstuff locally produced (score 1/3), which assess the system's role in supporting local economies and services.

The overall score of 3/5 suggests that the system’s social sustainability is medium, with strong job creation and biodiversity management but some concerns related to health and safety and stakeholder independence.

Environmental score: 2/5 Low

Economic score: 3/5 Medium

Social score: 3/5 Medium

↓

Overall score: 3/7 Medium-low

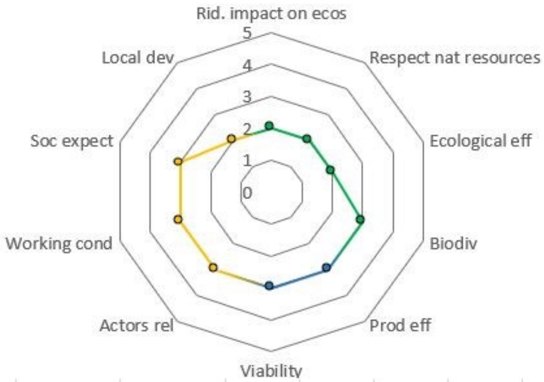


Figure 5.3: *Radar chart representing the scores of various sustainability criteria in the multicriteria assessment. Each axis corresponds to a different sustainability criteria, with qualitative scores ranging from 1 (low) to 5 (very high)*

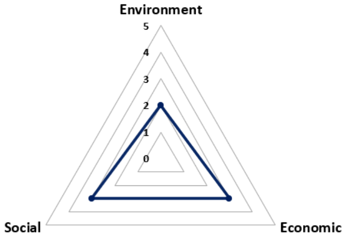
Overall Sustainability Score: 3 out of 7 (Medium-Low)

After aggregating the environmental, social, and economic dimensions, the system achieves an overall sustainability score of 3 out of 7, which corresponds to a medium-low level of sustainability. This score reflects the following:

- The **Environmental Sustainability** dimension, with a score of **2/5**, weighs down the overall performance. Key environmental indicators like nutrient emissions, energy consumption, and ecosystem impacts show poor performance, suggesting that the system has significant room for improvement in mitigating its environmental footprint.
- The **Social Sustainability** score of **3/5** shows that the system performs reasonably well in terms of employment conditions and biodiversity management, though some areas like health and safety and stakeholder relationships need improvement.
- The **Economic Sustainability** score of **3/5** reflects a system that is economically viable but faces challenges in profitability and cost efficiency, particularly regarding feed and labour costs.

The **overall score of 3 out of 7** (medium-low) indicates that while the system demonstrates some positive aspects, particularly in social and economic sustainability, its environmental performance significantly reduces its overall sustainability. To move toward a higher sustainability level, it would be necessary to focus on improving environmental impacts, particularly through better feed efficiency, reduced nutrient emissions, and more efficient resource use.

Table 5.2: *Breakdown of the overall sustainability assessment across three main branches: Environment, Economic, and Social. The figure inside the table represents a triangular radar chart displaying the system's performance across the three sustainability pillar. Each axis ranges from 1 (low) to 5 (very high)*

Overall sustainability	**Branch**	**Score**	**Criteria**	**Score**
Medium-low	Environment	Low	Reduce Impact on Ecosystems	Low
			Respect Natural Resources:	Low
			Ecological Efficiency	Low
			Biodiversity	Medium
	Economic	Medium	Production efficiency	Medium
			Viability	Medium
	Social	Medium	Actors relationship	Medium
			Employment and Working Conditions	Medium
			Meeting societal expectations	Medium
			Contribution to the local development	Low

5.4. Discussion and conclusions

The sustainability of aquaculture, particularly in systems such as those analysed here, presents a complex balance of environmental, economic, and social factors. Various indicators show how trade-offs must be made across these dimensions, reflecting the interdependencies and sometimes contradictory goals of aquaculture operations.

The environmental sustainability of the aquaculture system assessed in this study scores relatively low, particularly due to high environmental impacts such as nutrient emissions (total nitrogen emissions), global warming potential, and land competition. These findings align with research that emphasizes the environmental challenges of aquaculture, particularly related to feed conversion and nutrient waste (Le Feon et al., 2021). Furthermore, ecological inefficiencies, such as a high Fish-In-Fish-Out (FIFO) ratio, indicate that the farm relies heavily on wild fish stocks, contributing to broader environmental concerns about resource over-exploitation. To improve environmental performance, changes in feed composition and better resource management practices are necessary. Studies such as Maiolo et al. (2020) highlight the potential of using alternative proteins, such as insect meal, which could reduce the environmental footprint of feed production. This aligns with a broader push toward integrated multitrophic aquaculture (IMTA), which aims to improve ecological efficiency by recycling nutrients across different species (Knowler et al., 2020).

The economic sustainability of the system is moderate, with production efficiency scoring reasonably well. Indicators such as average sales prices and juveniles costs are favorable, but inefficiencies in feed conversion and energy use contribute to higher costs. As emphasized by Le Féon et al. (2021), production efficiency is critical for economic viability, particularly in competitive markets where cost efficiency and resource utilization directly impact profitability. The farm's internal rate of return (IRR) and net present value (NPV), however, suggest that there is still room for improvement in long-term profitability. Economic resilience can also be bolstered by reducing reliance on external subsidies and increasing production diversification, both of which can mitigate risks related to market volatility and input costs. Additionally, Colomb et al. (2012) emphasize the need for continuous innovation and adaptation, particularly in low-input systems like the one assessed here, which face challenges in both productivity and economic returns.

The social sustainability of the aquaculture system is also evaluated as medium, primarily due to moderate scores in employment and working conditions. The farm provides stable employment and fair labor conditions, but challenges remain in areas such as stakeholder relationships and local community development. Incorporating social life cycle assessment (S-LCA), as demonstrated by Bohanec et al. (2007), provides a comprehensive view of the farm's social impact, taking into account different social indicators. Ensuring better alignment between aquaculture practices and local development goals could improve both social acceptance and the farm’s integration within the community.

The DEXiAqua model, used to assess the farm, has proven effective in identifying key sustainability hotspots and trade-offs. By allowing the aggregation of environmental, economic, and social factors, it provides a balanced view of the system's strengths and areas for improvement. The model's flexibility allows it to be adapted to different contexts, but as noted by Sadok et al. (2009), the compensatory nature of such assessments means that deeper analysis at each aggregation level is necessary to avoid oversimplification and to pinpoint critical improvement areas.

In conclusion, the sustainability of the land-based aquaculture system for Sea bass and Sea bream presents a mixture of challenges and opportunities. While the system performs adequately in social and economic aspects, significant improvements are required in environmental performance to move towards a more sustainable operation. Feed efficiency, energy use, and nutrient management are key areas that need attention. Future innovations in feed technology, resource management, and integrated aquaculture practices could help the system achieve higher sustainability scores. Additionally, improving stakeholder relationships and strengthening local development contributions would further enhance the system's overall social impact. The DEXiAqua framework remains a valuable tool for providing comprehensive, multi-criteria evaluations that can guide sustainability improvements across aquaculture systems. This analysis also highlights the importance of using multicriteria decision support tools like DEXiAqua to provide a holistic assessment of sustainability. By considering environmental, economic, and social dimensions together, these tools help identify the key areas where interventions can lead to the most significant improvements, ultimately fostering more sustainable aquaculture practices. The DEXiAqua model also made it possible to analyse the various trade-offs of the systems. This often results in an equal score but with different individual indicator scores. This makes it possible to identify the best trade-off between the various sub-branches of sustainability. Finally, the model is based on a compensatory approach. This means that a very good score in a certain section of the sustainability branch can also compensate for a very low score in another section. For this reason, it is always essential to analyse all the various attributes and levels of aggregation comprehensively in order to be able to identify any critical points even in a "medium-high" overall score. The comprehensive and flexible structure of DEXiAqua allows for not only assessing present sustainability metrics but also for identifying potential improvements and innovations that could enhance future sustainability efforts, building on prior successful applications in similar contexts.

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CHAPTER 6 – Discussion

The discussion section of this thesis delves into the key findings and their implications, focusing on methodological advancements, potential impact reduction strategies, and future directions for sustainable aquaculture. Through a detailed analysis of the environmental and holistic sustainability assessments conducted on European Sea bass and Gilthead Sea bream farms, this section highlights the challenges and opportunities within the field. Particular attention is given to the refinement of the Life Cycle Assessment (LCA) methodology, the exploration of emerging environmental issues such as plastic pollution and antibiotic resistance, and the integration of innovative technologies to enhance aquaculture practices. These insights serve as a foundation for identifying areas requiring further research and development, ensuring the alignment of aquaculture with sustainability goals in an ever-evolving industry.

6.1. Methodological aspects

Aquaculture is one of the fastest-growing sectors in the agro-food industry and has experienced the greatest growth in the EU over the past 20 years. Although some LCA studies on aquaculture have been conducted since 2009 (Aubin et al., 2009), there are still relatively few LCA studies specifically addressing Sea bass and Sea bream production. This gap became evident in the first review presented in this thesis, where 12 LCA papers on Sea bass and Sea bream from the Mediterranean region were examined. Despite the economic significance of these two species, the limited number of studies highlights a clear opportunity for further research. Improving both the methodology and the development of impact mitigation strategies are key areas for future work.

Regarding methodology, one of the primary aspects requiring attention is the selection of an appropriate functional unit. In many agro-food processes, mass-based functional units are still the most widely used, both in aquaculture (Zoli et al., 2023) and in other agro-food sectors (Costantini et al., 2024; Zoli et al., 2021). However, there is a need to advance this approach. Since the primary purpose of aquaculture systems is to produce fish for human consumption, discussions on nutritional functional units are essential. Recently, several researchers have suggested that nutrient content should be factored into the determination of the functional unit for food products (Weidema & Stylianou 2019;). The most straightforward approaches focus on a single nutritional component, such as metabolic energy or protein (e.g., Sonesson et al., 2017). More complex functional units have also been proposed, incorporating nutritional profiling algorithms that summarize qualifying and disqualifying nutrients into a single score. Examples include the Weighted Nutrient Density Score (WNDS) developed by Arsenault et al. (2012). Drewnowski and Fulgoni (2008) reviewed several such nutrient profiling models, while van Dooren et al., (2016) noted that most share a similar structure. In fact, Van Dooren et al., (2016) pointed out that three key nutrients—total protein, essential fatty acids, and dietary fiber—correlate significantly with other essential nutrients and can be used to provide a comprehensive assessment. The use of gross or digestible energy content as allocation keys offers another promising alternative for defining functional units, particularly in seafood LCAs. These indicators provide a direct link between the energy embedded in the product and its environmental impact, enabling more nuanced comparisons across food systems. Metrics such as the Energy Return on Investment (EROI) further enhance this approach by evaluating the ratio of energy contained in edible seafood to the energy required for its production. In their comprehensive analysis of Peruvian seafood systems, Avadi and Freón (2015) propose an indicator framework that integrates CED and EROI as critical metrics. These indicators highlight the relationship between energy inputs (e.g., feed production, processing energy) and the energy available in the edible portion of seafood products. However, they also caution against the limitations of these energy-based indicators. They emphasize the challenges posed by variability in data quality, especially for agricultural and marine inputs used in feed production. Moreover, the study highlights the need to contextualize functional unit selection within the specific socio-economic and environmental goals of the assessment, as no single functional unit captures all dimensions of sustainability comprehensively. Another relevant indicator, the Protein-Per-Impact (PPI), measures the quantity of protein delivered relative to the environmental impacts incurred during production (Avadí & Acosta-Alba, 2021). PPI is particularly valuable for seafood systems, where the protein yield is a central function. By combining environmental impact data (e.g., greenhouse gas emissions, eutrophication potential) with protein outputs, PPI allows for an in-depth understanding of resource efficiency and environmental trade-offs in aquaculture. Furthermore, nutritional profiling models, like those proposed by Drewnowski and Fulgoni (2008), extend the functional unit discussion by integrating the nutritional quality of seafood products. The Nutrient Rich Food (NRF) index, for example, aggregates essential nutrient content while accounting for limiting nutrients, providing a balanced metric that aligns environmental assessments with dietary contributions. These methodologies underscore the need to move beyond conventional FUs and adopt frameworks that reflect both nutritional and energy efficiency

Although the debate remains open, it is clear that a functional unit based solely on mass is insufficient for systems designed to produce food for human consumption. Including at least one nutritional component would allow for more meaningful comparisons between different LCA studies on agro-food products. This approach, as advocated by several authors (Sonesson et al., 2017), should be adopted more widely in aquaculture as well.

Another possible choice for defining the functional unit could be an economic functional unit (e.g., 1 € income). With an economic functional unit, it makes it feasible to integrate the quantity and quality of a product into a single FU, broadly representing the function of agricultural commodities as economic goods and being appropriate for comparative LCAs (Sinisterra-Solís et al., 2023). Sinisterra-Solís et al. (2023) underscores the utility of the economic functional unit, particularly net value added (NVA), as a robust metric for assessing the environmental impacts of agricultural activities in a manner aligned with economic objectives. By expressing environmental impacts per € of NVA at factor cost, the analysis highlights the correspondence between resource use and economic performance across different agricultural holdings. This approach enables the integration of both qualitative and quantitative aspects of commodities, making it especially relevant for comparative analyses and policy development. However, the use of E-FU is not without challenges (Cerutti et al., 2014; Mouron et al., 2006). The reliance on economic indicators introduces uncertainty due to fluctuating market conditions, which can be mitigated by adopting multi-year averages. Additionally, the choice of economic indicator should align with the intended audience. For instance, profit-based metrics such as EBITDA (Earnings Before Interest, Taxes, Depreciation, and Amortization) could be more appropriate for farmer-focused studies, as it measures a company's operational profitability by excluding the effects of financing, taxes, and non-cash expenses. Customer-centric analyses, on the other hand, might benefit from price-based functional units.

Another critical aspect is the transparency of studies, particularly regarding life cycle inventory. The life cycle inventory phase is the most resource-intensive aspect of LCA studies, and data collection, often challenging, directly impacts the quality of the results. In a complex system like fish farming, capturing the full range of processes and interactions is always difficult. As reported in Chapter 3.1 and emphasized by Henrikkson et al., (2012), greater transparency is needed to allow for reproducibility and the development of aquaculture-specific databases. More extensive reporting of environmental flows within LCA studies can be achieved by providing supplementary materials or including reference numbers for background data sources. The future publication of guidelines specifically for performing LCA on aquaculture products will be an important step towards improving transparency and consistency across studies.

6.2 Improvements to reduce impacts

In terms of environmental impact, it was confirmed that feed plays a crucial role in the overall footprint of aquaculture systems. This has spurred research into alternative ingredients, especially to replace conventional protein sources like fish meal and soybean meal (Maiolo et al., 2020). A closely related aspect of feed management is the emissions resulting from fish metabolism. In all cases analysed in this thesis, these emissions were estimated using two models (one being an adaptation of the other) based on the mass balance of nitrogen and phosphorus compounds (Cho, 2004; Bureau and Hua, 2010). Essentially, both models operate in the same way, calculating all nutrient inputs and outputs. Specifically, solid and dissolved nitrogen (N) and phosphorus (P) emissions were estimated as the difference between the nutrients supplied to the fish through feed and the quantities assimilated during growth. Fish metabolism emissions play a significant role in water eutrophication. As highlighted by Bureau and Hua (2010), substantial reductions in waste outputs from fish farming operations can be effectively achieved by improving feed formulations to enhance the digestion efficiency and nutrient retention in fish. Waste output reduction could also be achieved through the use of dietary additives, such as enzymes or organic acids, and relatively simple processing techniques to improve the digestibility and availability of various feed ingredients, especially non-conventional ones. Furthermore, as also evidenced in this thesis, a novel approach to reducing the impact on water eutrophication could involve the development of an aquaponic system. The main findings demonstrated that significant improvements in these impact categories can be achieved through this innovative system. In particular, the analysed system rather than replacing feed, aimed to create a semi-self-sufficient system where a portion of the feed was produced within the system itself. Several challenges emerged during the development of the prototype (although this was not the direct focus of the thesis), as well as in applying LCA methodology to assess its impact. Nevertheless, the findings are consistent with the limited literature on aquaponics and IMTA systems (Bordignon et al., 2023; Jaeger et al., 2019), which highlight that these technologies, being still emerging, are difficult to evaluate and compare with traditional systems. However, it is clear that there is a significant imbalance between plant and fish production in integrated systems. While this offers advantages in terms of product diversification, it requires more complex infrastructure and management systems, leading to higher energy consumption.

Infrastructures are often overlooked in aquaculture LCA studies, as noted by Bohnes et al., (2019). However, farm engineering, alongside nutrition, genetic improvement, and disease control, plays a crucial role in improving both environmental and economic performance. To date, most marine aquaculture facilities use plastic nets, although alternatives like copper alloy nets exist. For this reason, Chapter 4.2 of this thesis explored the environmental impact of substituting traditional nylon cages with copper alloy cages in Sea bass and Sea bream farming. Although the comparison revealed trade-offs, mainly related to the recyclability of copper, it is important to note that no experimental trials were conducted on fish growth. Therefore, the analysis was based on a hypothetical scenario where fish growth rates were assumed to remain unchanged. Nevertheless, two studies have reported increased fish growth when copper alloy nets were used instead of traditional nylon or polyethylene nets, both in Atlantic salmon farming in Chile (Ayer et al., 2016) and in gilthead Sea bream farming in the Mediterranean (Yigit et al., 2018). Thus, the adoption of copper alloy nets could lead to an "indirect" reduction in environmental impact by lowering the consumption of production inputs, particularly feed, which would further enhance the environmental benefits of these alternative nets. This highlights that there is potential for improvement in this area, and that advances in precision fish farming tools could bring further benefits to the Mediterranean aquaculture sector.

Today, the most advanced precision farming tools are predominantly used in the Norwegian salmon industry, which is by far the most technologically developed sector globally. However, various tools are emerging to enhance technological control in aquaculture farms, including sonar, acoustic telemetry tags, and computer vision systems. As noted by Føre et al., (2018), many of these technologies are still in development but could soon be adopted in Mediterranean aquaculture. The analysed farms in this thesis were traditional operations representative of the standard Mediterranean setup, and none of them had installed precision farming tools. The adoption of such tools could offer significant opportunities for improvement.

This work underscores the importance of adopting a holistic approach to assessing the environmental impacts and overall sustainability of aquaculture systems. One of the key challenges is capturing the complexity and variability inherent in farming systems. While LCA provides valuable insights into the environmental footprint of fish farming, it cannot, on its own, guide decision-making or policy development. In the final chapter, LCA methodology was integrated into a multicriteria decision analysis (MCDA) framework, which explicitly considers multiple criteria to help decision-makers explore relevant choices by combining and integrating technical, social, and economic data, accounting for sector-specific and geographically specific factors. However, the tools developed with DEXi are not well-suited to spatial analyses. As qualitative methods do not allow for aggregation at larger spatial scales, further research and policy support are needed to promote comprehensive assessments and fully evaluate trade-offs. Moreover, the methodology is highly site-specific and requires adaptation for use in different contexts. Finally, there remains a need for further exploration of sensitivity analysis in this context.

6.3. Future perspectives

In this thesis, the application of LCA to the aquaculture sector followed general guidelines based on existing literature. However, this approach led to the exclusion of some newer impact categories, which are becoming increasingly relevant. One emerging concern is the environmental impact of plastic and microplastic pollution in marine environments. This is an issue that affects aquaculture both directly and indirectly and will undoubtedly require more attention in future analyses. Although the topic has not been extensively studied, plastic emissions from aquaculture involve multiple stakeholders throughout the product life cycle. For example, in marine aquaculture, numerous pieces of equipment—such as nets, buoys, ropes, and antifouling agents—are responsible for the release of plastics and microplastics into the environment (Tian et al., 2022; Zhu et al., 2019). Microplastics are also generated by antifouling agents (Loubet et al., 2022) and from other fishing activities

(Sanchez-Matos et al., 2024). According to recent studies (Napper et al., 2022; Syversen et al., 2022), microplastics may also come from fishing gear and FADs, depending on how this equipment is maintained and stored. Astorayme et al. (2024) reviewed the use of machine learning (ML) techniques, particularly deep learning (DL), to detect and quantify microplastics in aquatic environments using satellite and aerial images, as well as video recordings taken by drones. Additionally, Tian et al. (2022) developed the first framework for estimating plastic waste from aquaculture using a combination of satellite remote sensing, drones, questionnaires, and in situ measurements. Given the growing body of research on plastic emissions, their presence in various environmental compartments, especially in marine ecosystems, will undoubtedly become a key area for future inclusion in environmental impact assessments of aquaculture.

With the increase in production and farm intensity, the issue of antibiotic use and antibiotic resistance is also gaining attention. Although this aspect was excluded from the scope of this thesis, its importance is growing. Nyberg et al. (2021) reported that one of the few LCA studies in aquaculture that considered antibiotic toxicity (both human toxicity and ecotoxicity) was conducted by Henriksson et al. (2015). More recently, Sanchez-Matos et al., (2023) evaluated the environmental impacts of antibiotic use in rainbow trout farming through the use of recently developed antibiotic resistance (ABR) enrichment characterization factors (CFs) (Nyberg et al., 2021). Since ABR enrichment CFs are aligned with the USEtox method, the results for both toxicity and ABR enrichment were reported using default CFs from USEtox and Nyberg et al. (2021), covering a significant portion of antibiotics used in the studied systems.

Finally, as analysed in Chapter 5, it is essential not only to assess the environmental sustainability of aquaculture systems but also their economic and social sustainability. Often, improvements in one dimension are linked to trade-offs in another, particularly depending on the technological and geographical context. The approach taken by the DEXiAqua model used in this thesis is compensatory. This means that even if a system performs poorly in one of the three sustainability pillars, it can still achieve a good overall sustainability if it performs well in the other pillars. An alternative approach, which was not explored in this thesis, could involve defining minimum sustainability thresholds, below which a system would be deemed unsustainable, regardless of performance in the other pillars.

Mediterranean aquaculture, particularly Sea bass and Sea bream farming, is on the rise. Along with this growth comes an increasing need to develop new assessment systems and expand holistic evaluations to ensure sustainable development**.**

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CHAPTER 7 – Conclusions

This PhD thesis has explored the sustainability challenges and potential mitigation strategies in Mediterranean aquaculture, with a focus on Sea bass and Sea bream farming. The research employed Life Cycle Assessment (LCA) as a primary tool to quantify the environmental impacts of these species' farming systems, identifying critical hotspots such as feed production, energy consumption, and nutrient emissions.

The results indicate that, while Mediterranean aquaculture is expanding rapidly, it faces significant environmental challenges. Feed production, particularly the use of fishmeal and soybean meal, remains a major driver of environmental impacts, particularly concerning global warming potential and land use change. Land-based systems, though more controlled and less impactful in terms of nutrient discharge, present their own set of challenges, particularly higher energy demands, which increase their carbon footprint.

The study also highlighted the role of infrastructure in environmental performance, especially in sea-cage farming. Traditional polyethylene nets were compared with copper-alloy alternatives, revealing trade-offs between durability, biofouling prevention, and recyclability. While copper-alloy nets present potential environmental advantages due to their longer lifespan and lower maintenance needs, their adoption remains limited due to higher initial investment costs.

One of the key findings of this work is the importance of adopting a holistic approach to sustainability, integrating not only environmental factors but also economic and social dimensions. This was demonstrated through the application of the DEXiAqua model, which provided a multi-criteria assessment of aquaculture systems. The results showed that while the analysed system performed well economically and socially, their environmental sustainability was quite compromised.

Looking ahead, the thesis suggests several areas for future improvement. Feed efficiency and sourcing alternative ingredients could be potential mitigation actions. Moreover, adopting integrated multi-trophic aquaculture (IMTA) systems could enhance nutrient recycling, making aquaculture more ecologically efficient. The topic of using renewable energy and liquid oxygen is also a very hot issue for land-based facilities. However, the success of these solutions will depend on further technological developments and increased investment in infrastructure.

As Mediterranean aquaculture continues to grow, there is a pressing need for more sustainable practices to ensure the long-term viability of the sector. This thesis has provided valuable insights into current environmental impacts and highlighted potential pathways for reducing these impacts. However, achieving true sustainability in aquaculture will require continuous innovation, stronger regulatory frameworks, and a greater commitment to adopting advanced technologies, such as precision farming tools and alternative energy sources. Through the continued application of tools like LCA and multicriteria assessment models, the aquaculture sector can move towards more sustainable practices that balance environmental, economic, and social considerations.

Other research activities

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