

Journal Pre-proof

Life cycle assessment of seabass and seabream production in the Mediterranean area: A critical review

Michele Zoli, Lorenzo Rossi, Carlo Bibbiani, Jacopo Bacenetti



PII: S0044-8486(23)00354-X

DOI: <https://doi.org/10.1016/j.aquaculture.2023.739580>

Reference: AQUA 739580

To appear in: *aquaculture*

Received date: 23 November 2022

Revised date: 10 March 2023

Accepted date: 13 April 2023

Please cite this article as: M. Zoli, L. Rossi, C. Bibbiani, et al., Life cycle assessment of seabass and seabream production in the Mediterranean area: A critical review, *aquaculture* (2023), <https://doi.org/10.1016/j.aquaculture.2023.739580>

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2023 Published by Elsevier B.V.

Life cycle assessment of seabass and seabream production in the Mediterranean area: a critical review

Michele Zoli¹, Lorenzo Rossi², Carlo Bibbiani², Jacopo Bacenetti¹

¹ Department of Environmental and Policy Science- Università degli Studi di Milano

² Department of Veterinary Science - University of Pisa

Abstract

Background: In Mediterranean countries, the production of seabream and seabass has grown steadily over the last decades, and this trend is expected to continue. At the same time, sustainability has become a key question, and sustainable management strategies are needed to reduce the environmental impact of this sector. A holistic perspective is required to fully assess the environmental profile of fish production, and Life Cycle Assessment (LCA) is considered the most suitable approach for this purpose.

Scope and approach: This review aims to analyse all LCA studies regarding seabass and seabream farming in the Mediterranean area. In particular, the main methodological choices were analysed, the main critical points and gaps were identified, and the main hotspots and key results were highlighted.

Key findings and conclusions: The mass-based functional unit and the from-cradle-to-farm-gate system boundaries were selected in all studies. One of the main issues is the lack of transparency regarding some inventory data and sub-processes included in the assessment. The most common findings are the large environmental impact associated with feed and the large influence of the Feed Conversion Ratio (FCR) on environmental performance. However, further studies are needed to investigate this topic and to evaluate fish farming with the use of more sustainable feeds. Therefore, in the future, it will be

necessary to perform further LCA studies and, for an overall sustainability assessment, the energy, economic and social aspects will also to be increasingly taken into consideration.

Keywords

Life cycle assessment – aquaculture – seabass – seabream – environmental impact

Journal Pre-proof

1. Introduction

Fish and seafood are increasingly important food and protein sources for the growing world population. Seafood is often the major source of protein for people and an important source of highly nutritious foods (Cooney et al., 2021). It is frequently promoted as a sustainable alternative to red meat, which, for environmental and health reasons, is recommended to be restricted in a balanced diet (Scarborough et al., 2014). Historically, fishing has always been the main activity for the supply of seafood, but to meet the growing global demand, fishing is predicted to reach unsustainable levels. Nowadays, 35.4% of the fish stock is overfished (FAO, 2022). For this reason, seafood production has progressively switched to aquaculture, with a production growth in recent decades (Bohnes and Laurent, 2019).

In Mediterranean countries, aquaculture production has grown steadily in recent decades, and this trend is expected to continue (Bordignon et al., 2022). Currently, gilthead seabream (sp. *Sparus aurata*) and European seabass (sp. *Dicentrarchus labrax*) are the most commonly farmed species in the Mediterranean Sea, at a production of 520,000 tonnes and USD 2.58 billion in 2020 (FishStatJ, 2022). More than 95% of the world's seabream and seabass production comes from aquaculture, of which 97% is produced by Mediterranean countries (FishStatJ, 2022). The main producers are Turkey (which alone accounts for about half of the Mediterranean area's production with about 148,000 tonnes of sea bass and 109,000 tonnes of sea bream) and Greece (about 44,000 tonnes of sea bass and 62,000 tonnes of sea bream), whereas the main consumers are Spain, France, Italy, Greece and Turkey.

However, aquaculture systems, both inland and offshore, are subject of environmental concerns related to feed and energy consumption, the emission of nutrients and organic compounds into the water and, sometimes, the consumption of pesticides and antibiotics (Le Féon et al., 2021). Therefore, sustainable management strategies are required for an

environmentally sustainable development of the aquaculture sector (Børresen, 2013; Ababouch et al., 2015; Bordignon et al., 2023).

In December 2019, the European Commission launched the European Green Deal (European Commission, 2019), the EU's new growth strategy, which aims to cut pollution and carbon emissions, boost the efficient use of resources and restore biodiversity. The European Green Deal, the Farm to Fork Strategy (European Commission, 2020) and the strategic guidelines for a more sustainable and competitive EU aquaculture (European commission, 2021) emphasise the potential of aquaculture as a major contributor to a sustainable and responsible food system, in particular as a low-carbon footprint source of protein. The aim is to further boost low-environmental-impact aquaculture, such as the production of low trophic species (micro- and macroalgae), low-input production systems (such as filter feeders, e.g., molluscs), organic aquaculture and integrated multi-trophic aquaculture (IMTA) (Rosa et al., 2020). Moreover, fisheries and aquaculture are central to achieving food security as well as economic, social and environmental goals. Besides, the Sustainable Development Goal 14 (Conserve and Sustainably Use the Oceans, Seas and Marine Resources for Sustainable Development) has clear and important implications for fisheries and aquaculture.

For all these reasons, in the current economic and social context, the sustainable development of the aquaculture system is becoming more and more a priority (Marvin et al., 2020). Optimising and reducing system inputs, reducing energy consumption and, more generally, improving the efficiency of the entire system to improve the environmental performance of the sector are the primary goals (d'Orbcastel et al., 2009). To achieve them and to fully assess the environmental profile of fish production, a holistic perspective is needed. In this context, Life Cycle Assessment (LCA) is considered the most suitable approach for analysing a broad spectrum of environmental impacts (Guinée, 2002).

The LCA is a common approach for assessing the environmental impacts of products and services by analysing their environmental loads in a life cycle perspective, from the extraction of raw materials to their end of life. It is mainly applied in the quantification of different environmental impacts (impact categories, effects on the environment), the comparison among different products or different production systems and the choice among comparable products.

Although there are no specific guidelines for LCA application to aquaculture and the project AQUAPEF (Life AQUAPEF, 2018), which aims to promote the effective implementation of the Product Environmental Footprint in the Mediterranean aquaculture sector, LCA has already been widely applied to aquaculture since the early 2000s, and the number of LCA studies published in this field has increased in the last few years. This is also highlighted by previous LCA reviews in the aquaculture. For example, Aubin (2013) reviewed the LCA application in the aquaculture and fishery sector, aiming at providing an overview of its environmental impacts (Biermann and Geist, 2019). Pahri et al. (2015) analysed how natural and anthropogenic factors were managed in LCA studies focused on aquaculture. Bohnes et al. (2018) conducted a quantitative analysis on 65 LCA studies to explore which impacts can be identified as dominating and to compare different types of aquaculture systems. Bohnes and Laurent (2019) reviewed the methodological choices of LCA studies, provided a set of recommendations and outlined a research agenda to address the requirements for a more consistent LCA practice in the aquaculture. Finally, Henriksson et al. (2012) identified possible data gaps and provided recommendations for future development within this field of research. The authors concluded on a lack of transparency in the data used and reported a limited coverage in the number of impacts assessed by the studies and too narrowly scoped system boundaries, for which they provided a number of recommendations to future studies.

Although the aforementioned reviews provided insights to improve LCA studies in aquaculture, there are no reviews focusing on the application of the LCA approach to the Mediterranean aquaculture of seabass and seabream. Given the crucial importance of these species in the Mediterranean area, which is even destined to grow further in the future, the goal of the present study is to review the current knowledge on the environmental performances of seabass and seabream farming. In particular, it aims to

- Identify the aspects of seabass and seabream aquaculture that are primarily responsible for the impact;
- Summarise the main findings of LCA studies carried out;
- Analyse the LCA application to seabream and seabass aquaculture farm highlighting the main methodological concerns related to LCA application to this sector of aquaculture;
- Suggest future developments and research activities.

Based on the above mentioned goals, the review is organized as follow: Section 2 describes the methodology of the review, Section 3 summarizes the main descriptive characteristics of the farms analysed in the reviewed LCA studies, Section 3 reports the main LCA results (contributions analysis and environmental impact results), Section 4 describes how LCA approach was applied to the different farms, Section 5 critically discuss the LCA application in the different studies, Section 6 provides future perspectives for sustainability assessment of this aquaculture sectors.

2. Literature review methodology

The literature review was carried out using the database of Scopus and Web of Science™. The following keywords were combined: "LCA", "Life Cycle Assessment", "Seabass", "Sea bass", "*Dicentrarchus labrax*", "Seabream", "Sea bream", "Gilthead

seabream", "*Sparus aurata*"; we also combined the words "LCA", "Life Cycle Assessment" and "Aquaculture".

The 234 manuscripts identified were screened based on title and abstract. In particular, the following cut-off criteria were considered:

- The study should analyse, even partially, the environmental performance of the life cycle of seabream and/or seabass production using LCA in the Mediterranean area;
- The assessment must be carried out with a life cycle perspective;
- The study must be published in peer-reviewed journals. Thus, conference proceedings and book chapters were not considered.

It was not necessary to limit the reference period since the first study in line with our selection criteria was published in 2009. Therefore, the analysis regards manuscripts published from 2009 up to November 2022.

3. Characteristics of the analysed farms

In this section all the information related to the main characteristics of the analysed farms in the reviewed LCA studies is summarised. This would allow, in the following sections, to better appreciate the link between operational parameters and LCA results as well as to identify how the LCA approach is able (or not) to properly model aquaculture farms and their peculiarities. In detail, the location, the number and the type of farms, the size of the farms and other descriptive and productive parameters are reported.

3.1 Geographical location, number and type of aquaculture farms

The aquaculture farms including in the analysed studies are located in Greece (5 studies), Tunisia (3), Spain (2), Albania (2), Italy (1) and France (1) (**Fig. 1**). Among all the studies, just Kostantinidis et al. (2020) have analysed farms from two different countries (Greece and Albania), whereas all the other studies referred to a single country. It should be

highlighted that aquafarms in Turkey have not been analysed so far. Nevertheless, Turkey's aquaculture production accounts for about 50% of the Mediterranean production (FishStatJ, 2022), and its environmental impact should therefore be considered. Regarding the number of aquaculture facilities studied, some articles refer to a single farm (a case study), whereas few others have analysed several aquaculture farms (**Fig. 1**). For instance, Abdou et al. (2018) collected information from 18 different Tunisian aquafarms to perform a Principal Components Analysis (PCA), whereas 4 different Greek offshore farms and 3 packaging facilities were analysed by Konstantinidis et al. (2021a) and Konstantinidis et al. (2021b), respectively.

Most of the studies (10) analysed offshore farms characterised by floating circular sea cages (**Table S1** in the Supplementary Material). This type of plant represents the predominant aquaculture facility in the Mediterranean area, with more than 95% of production for both seabass and seabream (**Table S2** in the Supplementary Material).

These farms usually consist of several floating cages in which fish are raised from juveniles up to commercial size; all operations (e.g., feeding, maintenance) are conducted by highly skilled personnel with service boats (Cardia and Locatelli, 2015). Several other activities are conducted on land, such as post-harvesting operation and processing, feed storage, among others.

Among the analysed offshore farms, one (Mendoza Beltran et al., 2018) was coupled to a Pacific Oyster (*Crassostrea gigas*) production system in lantern nets in proximity to the fish cages (IMTA system).

Inland systems were analysed only by Jerbi et al. (2012), comparing a traditional raceway (TR) system with a cascade raceway (CR) system: the TR consists of concrete tanks in which water, directly pumped from the sea, flows by gravity and it is constantly discharged (flow-through systems); the CR is an alternative system in which water circulates by gravity in cascades, and water outflow from the upstream tank is the inflow of the next

downstream one. Using this technique, water can be aerated naturally without additional expenses since the cascade allows for a better aeration of the water (Jerbi et al., 2012). Both TR and CR can be considered open systems since no water is recirculated.

Since the growing cycle is similar, and the two species require similar environmental conditions, in the Mediterranean basin, the production of sea bass and sea bream is often conducted in the same farm. In fact, among the analysed systems, four are characterised by the co-production of sea bass and sea bream (Abdou et al., 2017, 2018; Kallitsis et al., 2020; Mendoza Beltran et al., 2018). However, four other studies refer to farms specialised in the production of sea bass only (Besson et al., 2017; García et al., 2019; Jerbi et al., 2012; Kostantinidis et al., 2020) and one of only sea bream (García et al., 2016), whereas in Kostantinidis et al. (2021a), the production of sea bream is coupled with meagre (*Argyrosomus regius*) production. Finally, Kostantinidis et al. (2021b) is the only study that refers exclusively to the packaging system of seabass and meagre.

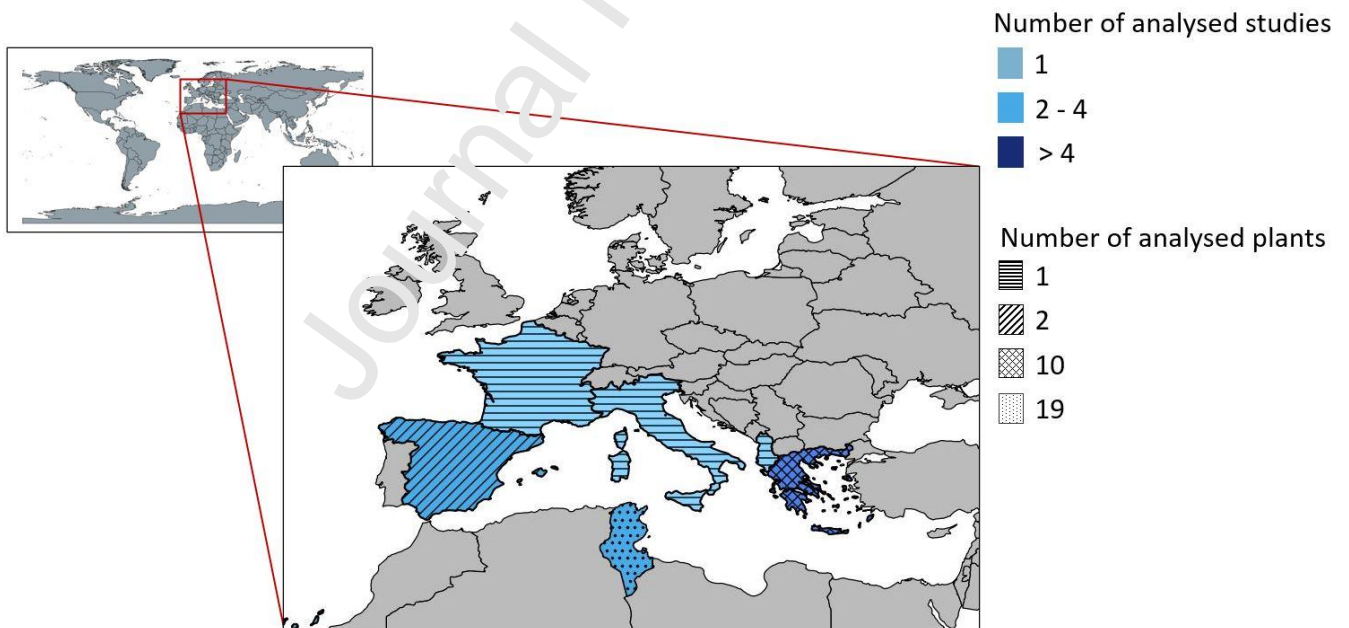


Figure 1: Geographic distribution of the revised studies and number of analysed farms.

3.2 Size of the farms

Farms of different sizes were analysed, both in term of cage number and annual production. Furthermore, some studies diversify the production between seabass and seabream, whereas others report only the total production of fish. In 4 out of the 12 studies, the description of the infrastructures is not reported, and 2 do not provide the cage size. The largest farm was analysed by Kallistis et al. (2020), with 6 cages for seabream of 5,600 m³ each and 64 cages for seabass of 5,800 m³ each, with a total of 404,800 m³. Abdou et al. (2018) selected 18 Tunisian intensive aquaculture farms, ranging from 47,000 m³ to 136,000 m³. The smallest farm, located in Evoikos Gulf (Greece), was analysed by Aubin et al. (2009) and is composed of 12 circular cages of 1,100 m³ each (13,200 m³ in total). The only inland farm (Jerbi et al., 2012) is composed of 89 parallel pipe-shaped concrete tanks of 280 m³ each for TR and 80 tanks of 200 m³ each for the CR system, with a total volume of 40,920 m³.

Consequently, the production of the analysed farm also varies greatly from 256 t/year for seabass (Aubin et al., 2009) to 2,500 t/year (Kallistis et al., 2020). Finally, in Kostantinidis et al. (2021b), three packaging farms of seabass and meagre had an average productivity of 4,015 t/year.

3.3 Other descriptive and productive parameters

Although the studies focused on different parameters and/or technical aspects (e.g., annual production, non-ingested feed, number of fingerlings, cages sizes, among others), feed conversion ratio (FCR) and rearing cycle duration had the greatest influence on environmental performance. **Table 1** provides a summary of the descriptive parameters of the analysed studies. The FCR indicates the amount of feed supplied divided by the biomass gained by the fish during a certain period. However, it does not account for the composition of the feed, the yield of fish (i.e., edible portion) or the nutritional quality of the final product. Despite the lower FCR of aquaculture compared to terrestrial systems, protein and energy

retention for aquaculture production are similar in livestock (Fry et al., 2017). This could be explained with the higher protein and energy requirements and their contents in feed compared to chickens, pigs and cattle (Fry et al., 2017). Therefore, the quantity of feed consumed is associated with the production of the system. Since all LCA studies report that the feed is one of the main factors responsible for different environmental impacts, the FCR is a key parameter for the analysis and interpretation of the results and therefore always reported in the considered studies. The average FCR of seabass is 1.99, whereas that for seabream is 2.09, according to the information given by the authors. The lowest FCR is reported by Abdou et al. (2018) (1.4 for seabream) and the highest by Mendoza Beltran et al. (2017), with an average of 2.8 for seabass and seabream. In the inland farm (Jerbi et al., 2012), the FCR is 1.89 and 2.11 (average of both species) for TR and CR, respectively.

The rearing cycle duration of the different aquaculture farms varies from 10 (Abdou et al., 2018) to 24 months (Jerbi et al., 2012; Kallistis et al., 2020). For this parameter, the authors do not differ between seabass and seabream. In half of the studies, fish are farmed up to a size of 400/450 g (Abdou et al., 2017; Besson et al., 2017; Garcia et al., 2016; Jerbi et al., 2012; Kostantinidis et al., 2020, 2021a). In one case, 600 g is reached (Kallistis et al., 2020). The juvenile's individual weight is more variable. In two cases, the initial weight is not reported, whereas in two studies, it is 2 g (Aubin et al., 2009; Kallistis et al., 2020), and in one study, it is 0.5 g (Garcia et al., 2019).

Another important parameter for the analysis is the mortality rate of fish. Nevertheless, 8 studies out of 12 do not report mortality rates, whereas in 4 different studies, the authors report different values: 10% for seabream (Garcia et al., 2016), 12% and 18.8 % for seabass (Jerbi et al., 2012; Kostantinidis et al., 2021) and 30% for both seabass and seabream (Mendoza Beltran et al., 2017); in the latter case, the mortality rate refers to fingerlings.

Table 1: Main descriptive parameters of the analysed studies.

Article	Rearing size (g)	Cycle duration (months)	FCR (kg feed/kg weight gain)		Production (t/y)	
			Seabass	Seabream	Seabass	Seabream
Abdou et al., 2017	4-400	18	1.88	1.85	630	1,470
Abdou et al., 2018	/	10-18	1.6-3	1.43	480-2,600	
Aubin et al., 2009	2-350	16	1.77	/	256	/
Besson et al., 2017	10-400	/	1.64-2.02	/	1,000	/
Garcia et al., 2016	12-450	18	/	2	/	1,000
Garcia et al., 2019	0.5-15 (juveniles) 15-500 (fish)	20	1.5 (juveniles) 1.9 (fish)	/	1,000	/
Jerbi et al., 2012	0-2 (hatchery) 2-75 (pre-growing) 75-375 (growing)	24	1.81-2.08	/	2,500	/
Kallistis et al., 2020	2-600	24	1.85	2.5	208	2,607
Kostantinidis et al., 2020	4-400	/	2	/	171	/
Kostantinidis et al., 2021a	/-437	23.8	2.14	/	1,534	/
Kostantinidis et al., 2021b	/	/	/	/	12,046	/
Mendoza Beltran et al., 2017	/	22	2.8		263	

4 Main findings of LCA studies

The two main outputs of a LCA study are the contribution analysis, i.e., the identification of the inputs and outputs mainly responsible of the environmental impact (environmental hotspots), and the quantification of different impact categories; besides, in the 4th step of LCA the achieved results are critically discussed (Notarnicola et al., 2015).

4.1 Contribution analysis

Regarding the contribution analysis, feed production is the main hotspot for Global Warming Potential (GWP) impact category and Acidification (A) in most studies. For the

GWP, in 9 out of 12 studies, the share of impact related to feed exceeded 60%, with a maximum of 93%. Nevertheless, in Kallistis et al. (2020), the feed impact was only 10% since the authors considered the absorption of CO₂ in the agricultural phase of the feed ingredients. In addition, they included packaging and delivery in the analysis, which account for 40% of the GWP. In Jerbi et al. (2012), the feed impacts were 18% and 23% for CR and TR systems, respectively, whereas the pre-growing phase had an impact of 51% (TR) and 40% (CR). Electricity has a relevant impact of about 30% for both TR and CR systems, underlining how electricity consumption is a relevant hotspot in inland system (Jerbi et al., 2012). In Kostantinidis et al. (2021b), for the packaging phase assessment, the main hotspots are electricity (about 39%) and EPS packaging of fish (about 50%).

For acidification, in all studies, the contribution of feed production is higher of 43%, except than in Jerbi et al. (2012) (23%), and Kostantinidis et al. (2021b), where the main hotspots are electricity and EPS packaging.

The emissions of nitrogen and phosphorus compounds into the environment are the main hotspots of eutrophication (from 3% to 93% of the impact) in all studies in which the CML Baseline method was used. However, in Kostantinidis et al. (2020; 2021a), with the Recipe method, the whole impact in FE and ME is largely related to feed production.

The high contribution of feeds is due to the inclusion of fish meal and fish oil as major ingredients. However, soybean meal, one of the most widely used plant-based protein sources in aquaculture, also has a high environmental impact (Garcia et al., 2016). Therefore, finding other sources of protein and lipids for fish feed is a challenge in aquaculture (Maiolo et al., 2020). By replacing marine-based ingredients with plant-based ingredients, the energy use can be reduced. However, Ellingsen and Aanonsen (2006) report that this trend can be counteracted by the energy consumption required for the cultivation phase and, above all, for soybean meal, the impact in terms of land use is high (Costantini et al., 2021; Silva et al., 2018). Basto-Silva et al. (2019) highlighted a tendency for

plant feed-based diets to have lower environmental impact scores than fish meal-based ones, even if all diets tested had the same order of magnitude. Several studies have also been carried out to test and assess the environmental impacts of alternative diets (Bartek et al., 2021; Glencross et al., 2020; Schade et al., 2020); however, so far, no LCA study regarding seabass and seabream production with an alternative feed or with an optimised feed distribution system has been conducted in the Mediterranean area.

Contribution analysis also highlighted the significant impact of energy consumption on environmental performance. Energy is required for a range of activities, including general system operation, harvesting, processing and transportation. Since fossil fuel consumption is of great concern, the use of renewable energy sources, such as solar or wind power, could be also seen as an alternative to improve the environmental profile (Aubin et al., 2013). Energy conservation at the farm scale and replacement of fossil fuels by renewable sources must therefore be supported (Jerbi et al., 2012). As reported by Aubin et al. (2009), a cage system requires less energy than an inland system, despite frequent shipping from shore to the cages. However, the energy impact is the least investigated one. In particular, the absence of detailed and updated information regarding energy needs, installed powers and load curves is an objective limit to the possibility of optimising the systems both from an economic and environmental point of view. It is also necessary to consider that whilst in offshore systems, energy consumption is limited to diesel and lubricant oil for boats, in inland farms, there are several pumping systems, aerators/mixers and oxygen supply distribution devices that are energy-demanding. In light of the recent increases in the cost of energy, the energy analysis of farms has particular importance and represents the starting point for further process optimisation.

4.2 Impact assessment results

With regard to the quantification of the different impact categories, the results show great variability due to both different farm characteristics and different methodological choices, as well different modelling methods. **Table 2** reports the GWP values of the reviewed studies, while the results of the other more analysed categories (Acidification, Eutrophication, Freshwater eutrophication, Marine Eutrophication and Cumulative Energy Demand) are reported in the supplementary materials (**Table S3**).

Table 2: Environmental results for GWP (kg CO₂ eq) expressed per 1 ton of live fish weight.

Article	Global warming potential (kg CO ₂ eq/ton of live fish weight)	
	Sea bass	Seabream
Abdou et al., 2017	3,782	3,669
Abdou et al., 2018	from 3,421 to 4,437*	
Aubin et al., 2009	3,601	/
Besson et al., 2017	From 2,960 to 3,636*	
Garcia et al., 2016	/	7,124
Garcia et al., 2019	7,293	/
Jerbi et al., 2012	TR: 11,087 CR: 17,449	/
Kallistis et al., 2020	1,235**	1,118**
Kostantinidis et al., 2020	Not reported	
Kostantinidis et al., 2021a	Not reported	
Kostantinidis et al., 2021b	Not reported	
Mendoza Beltrán et al., 2017	Monoculture system: 11,320* IMTA system: 11,710*	

*average value for ESB & GSB; **absorbed carbon during fish feed production was considered

The lowest carbon footprint (1,235 kg CO₂ eq/ton of live fish weight) was reported by Kallistis et al. (2020), but, as mentioned before, they took into account the CO₂ absorbed during feed production. Jerbi et al. (2012) reported the highest carbon footprint (17,449 kg CO₂ eq/tonne of live fish weight), mainly due to both a high feed wasted and the high energy consumption required by an inland fish farm.

However, Mendoza Beltran et al. (2012) reported an impact of 11,710 (IMTA system) and 11,320 kg CO₂ eq/ton of boxed and gutted fish (monoculture) that is the highest value among offshore farms: in this case, the authors also took into account fish processing after harvesting, which has an impact of about 35% of the GWP. This is also the only case in which an IMTA system has been analysed; however, the small difference between the monoculture system and the IMTA system can be partly explained by the production scale: the production of 4 t of oyster annually is a very low value compared to 240 t of fish. Moreover, the additional impact due to the construction activities and the management of IMTA system must be considered.

Although it was analysed in only five studies, the cumulative energy demand (CED) is an impact category that well explains the large amount of energy required for aquaculture farms. Feed production, fuel and electricity are the main hotspots in this impact category. However, even in this case, there are some different results among the studies: Abdou et al. (2017 and 2018) and Aubin et al. (2009) report a similar CED value (from 44,232 to 57,198 MJ per ton of live fish weight), whereas in Garcia et al. (2016) the CED was 80,000 MJ per ton of live fish weight. In these cases, the main hotspot was the production of feeds (from 69% to 79%), whereas in Garcia et al. (2016), feed and fuels both had an impact of approximately 50%. In this regard, the authors reported a diesel consumption of 444 kg per ton of live fish, which is very high in comparison with that, for example, reported by Kallistis et al., (2020) of 45.75 kg and by Kostantinidis et al., (2020) of about 23 kg. In addition, in Jerbi et al. (2012), the CED was 175,000 MJ per ton for TR and 280,000 MJ per ton of live fish weight for CR. The contribution analysis of the CED shows that more than half of the impact was due to the pre-growing phase (Jerbi et al., 2012).

Since most of the reviewed LCA studies selected a mass-based FU, the environmental performances are necessarily related to the productivity and input efficiency. The latter is mainly related to FCR and energy consumption, suggesting an emphasis on the

development of more energy-efficient forms of aquaculture, generating greater returns while minimising their polluting emissions (Aubin, 2013). One of the main objectives for the aquaculture farms is to decrease feed wastage, improving feeding efficiency and feed composition to decrease the FCR.

5. LCA approach application

The purpose of this section is to analyse how the LCA approach was applied in the reviewed studies with a focus on the different steps of a LCA study, as identified by the ISO 14040 and 14044 standards. (ISO, 2006; ISO, 2018). Even if originally developed for industrial processes, in the last years LCA is more and more applied also to agricultural sectors (Notarnicola et al., 2015; Lovarelli et al., 2017). Based on the inputs (e.g., production factors used) and outputs (useful products, co-products and by-products, wastes and emissions into the environment), LCA quantifies the potential environmental impact of a product, a process or a service. Defined by the ISO standards 14040 and 14044, LCA involves 4 steps: (i) Goal and Scope involving the identification of the geographical scope, the target audience as well as the definition of the functional unit and system boundary, (ii) Life Cycle Inventory where the data about the energy and material flows between the analysed system and the environment, (iii) impact assessment during which the inventory data are converted in environmental impact and, (iv) interpretation.

The main review outcomes about the LCA application in the reviewed LCA study focused on the seabream and seabass aquaculture farm are reported in **Table 3** and are discussed in the following subsections.

Table 3: Main methodological aspects according to the ISO 14044 and ISO14040 of a Life Cycle Assessment of the analysed studies.

Article	Functional unit	System boundaries	Databases	Method	Impact categories
Abdou et al., 2017	1 ton of live-weight fish	Cradle to gate	Ecoinvent	CML2 Baseline 2000	A, E, GWP, LO, NPPuse, CED, Suse
Abdou et al., 2018	1 ton of live-weight fish	Cradle to gate	Ecoinvent	CML2 Baseline 2000	A, E, GWP, LO, NPPuse, CED
Aubin et al., 2009	1 ton of live-weight fish	Cradle to gate		Not reported	A, E, GWP, NPPuse, CED, WD
Besson et al., 2017	1 ton of live-weight fish; Farm per year	Cradle to gate	Ecoinvent	CML2 Baseline 2000	A, E, GWP
Garcia et al., 2016	1 ton of live-weight fish	Cradle to gate	Ecoinvent – Agri-footprint – LCA Food DK	CML-IA Baseline	A, E, GWP, CED, AD, OD, PHO
Garcia et al., 2019	1 ton of live-weight fish; 1 ton of fingerlings	Cradle to gate	Ecoinvent – Agri-footprint	CML-IA Baseline	A, E, GWP, AD, OD, PHO, AD-ff, HT, MEx, FEx, Tex
Jerbi et al., 2012	1 ton of live-weight fish	Cradle to gate	Ecoinvent – Buwal 250	CML2 Baseline	A, E, GWP, LO, NPPuse, CED, WD
Kallistis et al., 2020	1 ton of fish at end-consumer market; 100 g edible protein	Cradle to gate	Ecoinvent	CML Midpoint	A, E, GWP, AD, OD, PHO, HT, MEx, Tex
Kostantinidis et al., 2020	1 ton of feed; 1 ton of fish in isothermal bins	Cradle to gate	Ecoinvent – Agri-footprint – Agribalyse	Recipe 2016 (H) Midpoint	A, GWP, LO, WC, OD, Irad, OF-hh, PM, OZ-te, FE, ME, Mex, FEx, Tex, HCTx, HnCTx, MRS, FRS
Kostantinidis et al., 2021a	1 ton of fish fully packaged	Cradle to gate	Ecoinvent – Agribalyse	Recipe 2016 (H) Midpoint	A, GWP, LO, WC, OD, Irad, OF-hh, PM, OZ-te, FE, ME, Mex, FEx, Tex, HCTx, HnCTx, MRS, FRS
Kostantinidis et al., 2021b	1 ton of live-weight fish	Gate to gate	Ecoinvent – ELCD (JRC-EU)	Recipe 2016 (H) Midpoint	A, GWP, LO, WC, OD, Irad, OF-hh, PM, OZ-te, FE, ME, Mex, FEx, Tex, HCTx, HnCTx, MRS, FRS
Mendoza Beltran et al., 2017	1 kg of boxed and gutted fish	Cradle to gate	Ecoinvent	CML-IA Baseline	A, E, GWP, LO, AD, OD, PHO, AD-ff, HT, FEx,

Note: A: Acidification; E: Eutrophication; GWP: Global warming potential; LO: Land occupation; NPPU: Net primary production use; CED: cumulative energy demand; SU: Sea use; WD: water depletion; AD: Abiotic depletion; OD: ozone depletion; PHO: photochemical oxidation; AD-ff: Abiotic depletion fossil fuel; HT: Human toxicity; Mex: marine ecotoxicity; FE: Freshwater eutrophication; ME: Marine eutrophication; FEx: Freshwater ecotoxicity; Tex: Terrestrial ecotoxicity

5.1 Goal and scope definition

The LCA is applied to case studies in different geographical contexts and in different sizes farms: in particular, seven applied LCA to case studies to quantify the environmental impact of production and identify the main sub-processes responsible for the impact. Among these studies, Abdou et al. (2017) and Kallistis et al. (2020) deal with both of species, Garcia et al. (2016) only with seabream and Konstantinidis et al. (2020) and Garcia et al. (2019) only with seabass. Most of the LCA studies aim to describe the environmental performances of sea bass and sea bream production, although it is also possible to identify specific other purposes among the various studies. Garcia et al., (2019) also aimed to quantify the environmental impact of fingerlings. Kostantinidis et al. (2021a) (2021b) investigated a comparison between seabass and meagre: the first study also analysed the environmental performances of three different size feeds, whereas Konstantinidis et al. (2021b) is the only study with an in-depth analysis of the packaging phase. In detail, they quantified and compared the environmental impact of three different seabass and meagre packaging farms, proposing a reasonable scenario for environmental impact minimisation. Other studies have different goals: Aubin et al. (2009), Jerbi et al. (2012) and Mendoza Beltran et al. (2017) compared the environmental performances of different farming systems. Whilst Aubin et al. (2009) characterised the environmental impacts of different carnivorous fish production systems (seabass, rainbow trout and turbot), using three case studies to highlight how they depend on the aquatic environment, Jerbi et al. (2012) compared the impacts of TR system and a CR system, and Mendoza Beltran et al. (2017) compared traditional cage farming with an IMTA system coupled with oyster production. Abdou et al. (2018) performed a Principal Components Analysis (PCA) and Hierarchical Clustering on Principal Components (HCPC), whereas Besson et al. (2017) conducted a

bioeconomic analysis. In particular, Abdou et al. (2018), using data from 18 aquaculture farms, combining a LCA study with a PCA and a HCPC, revealed a high correlation between rearing practices and impacts. Besson et al. (2017) studied how production quotas affect economic profitability and the environmental impact and combined bioeconomic modelling with LCA to calculate the economic and environmental values of thermal growth coefficient (TGC) and the feed conversion ratio (FCR).

Regarding the target audience although the only study directly addressed to policy makers is Besson et al. (2017), the results obtained from LCA studies, as also reported by some studies (Abdou et al., 2017; Abdou et al., 2018; Kostantinidis et al., 2020) could provide information to support decision-making and investigation of ways to improve mitigation strategies to enhance aquaculture sustainability. Moreover, as EU policies are increasingly focused on sustainability, the results of the studies could be useful to farmers to reduce the environmental impact of production. Finally, a more sustainable fish production could also bring additional benefits from an economic point of view as "sustainability" is an increasingly requested feature also by consumers.

4.1.1 Functional unit

According to ISO 14041 (ISO, 2018), the functional unit (FU) is the reference unit used to quantify the performance provided by the evaluated product, process, or service. The FU shall be measurable and consistent with the goal and scope of the study. At the same time, there must be an agreement between the FU and the system boundaries considered.

Regarding the selection of FU (**Table 3**), all studies selected at least one mass-based FU. In 8 out of 12 studies, the authors refer the environmental impact to 1 ton of live weight of fish, this means that these studies are limited to the delivery of raw fish at the farm gate (or at the shore for sea cages).

Although the functional unit is based on mass, there are differences in the other four studies:

- Kallistis et al. (2020) selected 1 ton of fish at an end-consumer market. Furthermore, the impact was also reported per 100 g edible protein to enable comparisons with other protein sources;
- Mendoza Beltran et al. (2017) expressed the impact per 1 kg of boxed and gutted fish; based on this, 0.04 kg corresponds to gutted packed fish and 0.96 kg to whole boxed fish;
- Kostantinidis et al. (2021a) selected 1 ton of harvested fish in isothermal bins transported to the packaging gate for the quantification of all environmental impacts. The authors also performed an LCA of three different feeds, choosing 1 ton of feed as FU;
- Kostantinidis et al. (2021b) (the only study that analysed the packaging phase) selected 1 ton of fully packaged fish as FU.

4.1.2 System boundary

Several processes constitute the life cycle stages of an aquaculture production system. As suggested by Bohnes and Laurent (2019), they can be divided as follows: (I) fry production, (II) infrastructure and equipment, (III) feed production, (IV) fish production, management and harvest, (V) fish processing and packaging, (VI) distribution, (VII) consumption and (VIII) seafood end-of-life (**Fig. 2**). All these elements should be included in an LCA to ensure a complete life cycle evaluation. However, the analysed LCA studies do not include all these stages in the system boundary (**Table 3**). Precisely, 11 out of 12 studies applied a “from-cradle-to-farm-gate” perspective; thus, the operations from the extraction of raw materials to the capture of the fish are included in the assessments. However, although the choice is the same, among the different studies, some differences between the operations included or excluded in the analysis can be identified:

- Feed production, farm management with the related energy consumption and the emissions due to fish metabolism are included in all studies;
- Infrastructures and equipment are also included in the analysis (10 out of 12 studies), although the description often lacks details. Some studies include these inputs without mentioning how they are modelled, whereas others involve construction and fabrication but exclude maintenance and disposal. Other studies report more detailed information (e.g., fleet composition, life span, materials). Kostantinidis et al. (2021a) and (2020) excluded infrastructures from the assessment, but, in the latter case, they included the use and maintenance of the equipment for daily operations in the company.

Aubin et al. (2009), Besson et al. (2017), Garcia et al. (2016) and (2019), Kallistis et al. (2020), Kostantinidis et al. (2021b) and Mendoza Beltrán et al. (2017) excluded fry production from system boundaries. The main difficulty in including this sub-process in the system boundaries is that fries are often purchased from other highly-specialised companies with complex dedicated facilities. Even when fry production was included, there was a great variability in the modelling (e.g., different initial rearing weights, inclusion of transport), and it was included only in Abdou et al. (2017 and 2018) and Jerbi et al. (2012).

Mendoza Beltrán et al. (2017) applied a "cradle-to-gate" perspective, considering as "gate" the gate of fish packaging facility, whereas Kallistis et al. (2020) is the only work that also included the delivery phase in the system boundaries.

Finally, Kostantinidis et al. (2021b) selected the "gate-to-gate" perspective, only focusing on the packaging stage.

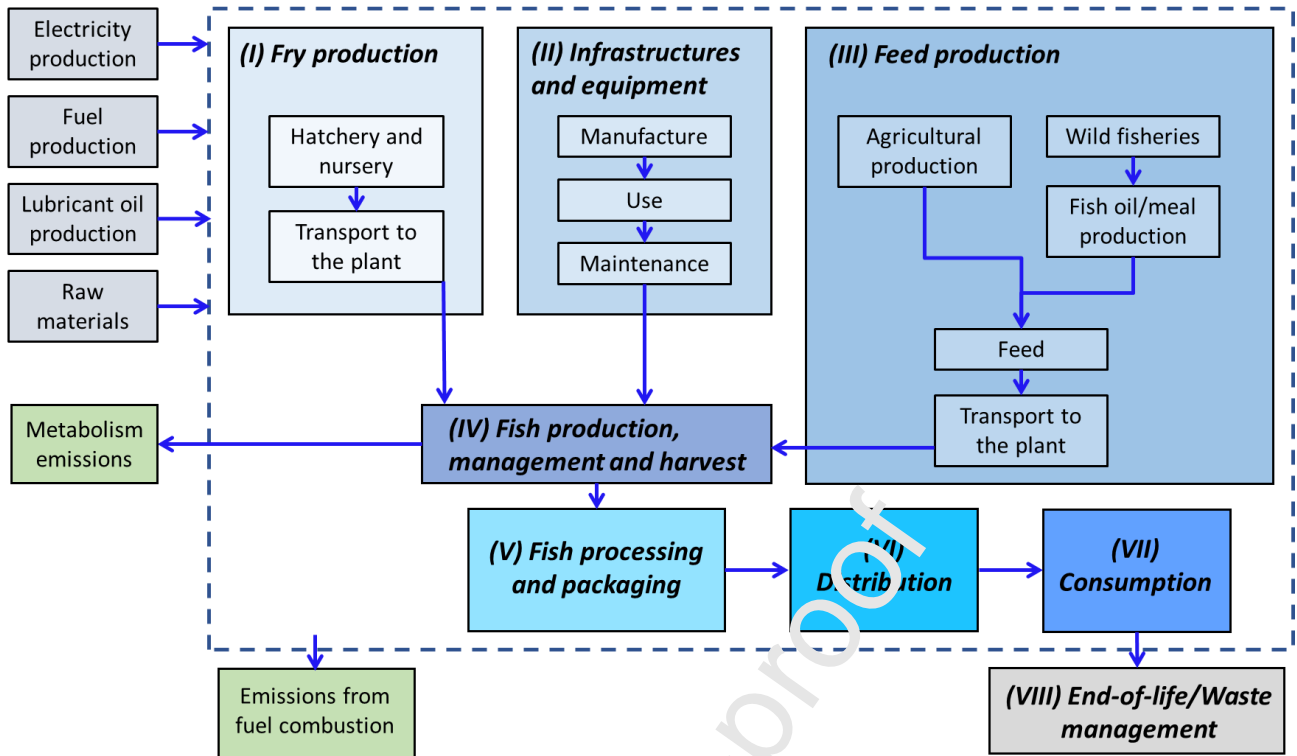


Figure 2: Life cycle stages of seabream and sea bass aquaculture production systems. The standard life cycle of sea bass and sea bream production is divided into 8 subsystems: (I) fry production: including all hatchery operations and the supply of juveniles by the aquafarm. (II): infrastructure and equipment: including the manufacture, use and maintenance of all infrastructure and equipment required in the aquafarm. (III) Feed production: includes all operations for the production of the aquafeed, starting with agricultural production for plant ingredients and with fishing for fish ingredients, and ending with the transport of the feed to the aquafarm. (IV) fish production, management and harvest: includes all farm management operations such as sowing of fry at sea, fish movement, feed distribution and harvesting at the end of the cycle; (V) fish processing and packaging: including fish processing, size division and packaging; (VI) distribution: including the distribution of confiscated fish on the market. (VII) consumption: including the consumption of the fish by consumers. (VIII) end of life/waste management: including all disposal operations after consumption. Common inputs in all sub-systems are shown in grey in the top left-hand corner. Then, within each subsystem, the main processes are reported.

5.2 Life Cycle Inventory

The LCA requires a broad data inventory to reflect production system complexity. The Life Cycle Inventory (LCI) is usually made using both primary and secondary data. The first are data directly collected by means of measurements, surveys, questionnaires and interviews, whereas the latter are derived from databases and literature and/or are estimated using models.

Regarding the consumption of electricity and diesel for the management of the aquaculture farms, all studies refer to primary data provided directly by the companies and collected mainly by means of interviews and questionnaires.

Referring to the feed, five studies (Besson et al., 2017; Jerbi et al., 2012; Kostantinidis et al., 2021a; Garcia et al., 2019; Kostantinidis et al., 2020) used primary data about the quantity supplied, the feed ingredients and the inclusions of the ingredients, whereas Mendoza Beltran et al. (2017) and Kallistis et al. (2020) used literature data. Only Kostantinidis et al. (2020) reported this different information transparently, whereas in the other studies, the data, in particular the inclusion of ingredients, were omitted for confidential reasons. Abdou et al. (2017 and 2018) used primary data for the quantity of supplied feed and ingredient composition, but the majority of the studies estimated feed composition through a centesimal analysis, which reflects the percentage of inclusion of various ingredients based on macronutrients (e.g., proteins and lipids) and energy content. Garcia et al. (2016) established a standard feed based on the information provided by fish feed producers and confidential consultations; only Aubin et al. (2009) clearly report all data but do not mention the source.

Concerning nutrient emissions, all studies used secondary data. Most of the reviewed studies (Besson et al., 2017; Garcia et al., 2016; Garcia et al., 2019; Kallistis et al., 2020; Kostantinidis et al., 2020, 2021a) report only total nitrogen and total phosphorus emitted, whereas others (Abdou et al., 2017a, 2018; Aubin et al., 2009, Jerbi et al., 2012) distinguish

between solid and dissolved nitrogen and phosphorus. In all, studies N and P emissions were estimated. In particular, 8 out of 12 studies used the mass balance model proposed by Cho and Kaushik (1990). In this model, waste output from the fish operation can be calculated using principles of nutrition and bioenergetics. Solid and dissolved nitrogen and phosphorus are estimated on the basis of the difference between the quantities of nutrients supplied to the fish through feed and the quantities assimilated during growth. The solid and dissolved fractions were quantified by considering the digestibility of the nutrients, the body composition of the fish, the amount of feed not ingested, the mortality of the fish and the composition of the fry. This modelling approach was previously adapted and validated for different fish species (Abdou et al., 2017; Bureau et al., 2003) and was also used in previous LCI studies of fish-production systems (Aubin, 2014; Aubin et al., 2009; 2006). Mendoza Beltran et al. (2017) predicted N and P emission using the Farm Aquaculture Resource Management (FARM) model (Ferreira et al., 2007; Cubillo et al., 2016). Among the various applications and purposes for which it was conceived, the FARM model allows to carry out an environmental assessment of farm related eutrophication effects (Ferreira et al., 2012).

No quantitative data regarding hatchery, fingerling stock maintenance as well as phytoplankton and zooplankton production are reported in the literature. The hatchery stage for seabass and sea bream often occurs in intensive systems with full control of abiotic parameters and feeds. Regarding the diet, larvae rely on live feed (i.e., microalgae and zooplankton mass culture), and feeding is conducted on site (Conceição et al., 2010). Abdou et al. (2017 and 2018) provide a list of considered sub-processes and data regarding the hatchery, but no quantitative data. In four studies, fry production was excluded due to a lack of data, whereas Kostantinidis et al. (2020 and 2021a) include fingerlings but do not report any data. Garcia et al. (2019) report a specific LCA regarding fingerlings. In detail, they considered this stage of life cycle by modelling the rearing of fingerlings from 5 to 15 g in an inland facility with pumped seawater and injected oxygen. The functional unit was 1

kg of juveniles. They also reported the amount of feed (1.5 kg per FU) used in this phase and its characteristics and estimated specific oxygen consumption (1,151 g O₂ per FU) and the electric energy consumed (8.18 kWh per FU) in the pumping of water to the culture tanks. This is the only study that reports quantitative data regarding fry production.

Infrastructures and equipment are another controversial aspect for the LCI. The review shows that 10 out of 12 studies include infrastructures and equipment in the analysis. However, the used data and their type are often undisclosed. Abdou et al. (2017 and 2018) included sea cages, boats, buoys and anchors as well as a Zodiac boat, but no quantitative data or other information are reported. Besson et al. (2017) consider the construction of a building of 650 m² as a shed for inland storage, with a life span of 30 years; in this study the authors list several equipment types, but only the carbon footprint of the construction of 1 m² of buildings and the production of all equipment needed at farm level without inventories are reported. In Garcia et al. (2016 and 2019), there are inventory primary data regarding the infrastructures (cages, consisting of the floating ring and nets and the mooring system). Jerbi et al. (2012) report primary data regarding the amount of steel and cement (respectively 41–91 and 146–325 kg per ton of seabass) for the construction of the raceways. Finally, Kallistis et al. (2020) and Mendoza Beltran et al. (2017) only include sea cages using secondary data from databases.

In terms of secondary data, the most used database was Ecoinvent (used in all studies) (Moreno Ruiz et al., 2016; Wernet et al., 2016), Agri-footprint (Blonk Consultants, 2014) was used in three studies and AgriBalyse (AgriBalyse, 2017) in two studies. The LCA food DK (Denmark), Buwal 250 (Prè Consultant, 2004) and ELCD (JRC-EU) databases are also cited at least once.

5.3 Impact assessment

To convert inventory data into different impact categories (effects on the environment), different methods with different characterisation factors can be used. The two used methods are the CML method (Guinée et al., 2002) (eight studies) and the Recipe method (Goedkoop et al., 2008) (three studies), whereas one study did not provide information about the method (**Table 3**). Global warming potential (GWP), Acidification (A) and Eutrophication (E) are the three impact categories analysed in all 12 studies. However, three studies that used the Recipe method (Kostantinidis et al., 2020; 2021a; 2021b) differentiated eutrophication in freshwater eutrophication (FE) and marine eutrophication (ME). Finally, no studies investigated the water footprint of the production. To this purpose, only two studies (Aubin et al., 2009; Jerbi et al., 2012) considered the water dependence impact categories. This last represents the water input relative to fish biomass production systems: for inland systems, it refers to the diverted or pumped water from a river, and for sea-cages systems, it refers to the rearing volume and the average water current (Aubin et al., 2009).

5.4 Discussion on methodological choices and unsolved issues.

In this sub-section, the main methodological choices made within the reviewed studies will be critically discussed providing useful insights for future LCA studies.

A comparison among the results of LCA studies should be made on the base of the same FU and methodological choices. However, in this regard it must be considered that the choice of the FU as well as the definition of the system boundaries depend on the purpose of the study. Consequently, this leads to a lack of consensus on the FU choice and reduces the possibility to compare the results from different studies (Aubin, 2013; Cao et al., 2013). Among the different mass-based functional units, mass of live weight is the most used one. Nevertheless, this FU could be misleading when different species are compared because

the nutritional value of the products and/or the yield at slaughter may differ by an order of magnitude. To overcome the latter issue, an alternative mass-based FU could be kg of fish slaughtered, as proposed by Mendoza Beltran et al. (2017). However, Bohnes and Laurent (2019) highlighted that a mass-based FU does not reflect the actual function of seafood (i.e., to provide nutritional benefits to consumers). For this purpose, Sonesson et al. (2017) recommended to define the FU of LCA studies in aquaculture considering nutritional criteria, such as protein or energy content (Sala et al., 2017).

Besides the FU, the system boundary definition also represents a source of uncertainty. The choice of system boundaries should be in accordance with the goal of the study, and the criteria used to establish system boundaries should be identified and explained (ISO 14044 2006). The inclusion of all the elements that can affect the environmental impact is a prerogative to conduct a complete LCA (Bohnes and Laurent, 2019), and it is important to include all steps to distribute the environmental loads in the best way.

Data collection is time- and money-consuming because the amount and the quality of the data needed for LCA comes from different stakeholders (e.g., farmers, fisheries, feed producers) and could involve confidential information (e.g., feed composition as well as antibiotic and pesticide application) (Samuel-Fitwi et al., 2012). The latter aspect explains the difference among LCA studies and sometimes the lack of transparency of the studies. Heriksson et al. (2012) underlined that in many studies, it is not clear whether background databases were used or whether real foreground data (site-samples) were collected. Besides this, it is often unclear which processes were retrieved from the databases. A mix of datasets from different sources is often used, some of which may be more precise than others (Ziegler et al., 2016). There is a lack of transparency also about the cut-offs criteria used for the building of inventories.

Regarding the quality of inventory data, the review highlights that good-quality data are generally used for feed formulation, nutrient emission and energy consumption, whereas information regarding the nursery phase, juveniles, infrastructures and equipment are often fragmented. In detail, Kallitsis et al. (2020) report that the environmental impacts of the hatching and nursing phases are insignificant compared to those of the rearing operation. This assumption is further supported by Silvenius et al. (2017), who, focusing on rainbow trout production, reported a negligible contribution of the hatchery to the life cycle climate impact and a 2% contribution to the eutrophication impact. On the other hand, in other studies (Abdou et al., 2017, 2018; Garcia et al., 2019), the impact share due to fingerling production ranged from 4% to 15% for acidification, from 3% to 12% for global warming potential and from 6% to 9% for TCED; it was about 23% for MAE. Further studies are required to fill this gap.

Concerning infrastructure and equipment, there is no consensus about their inclusion in the system boundary and on how to model their use. The information that would be important for the purposes of an LCA study refers to their manufacturing (e.g., mass, material composition, lifespan), use (e.g., annual use, working load), maintenance and disposal. Unfortunately, none of the studies reported all this information at the same time. Among these factors, net management plays a priority role as the net has a very short lifespan compared to the other aspects that make up the system, and it is the structure that requires more interventions, in particular regarding washing, the application of antifouling compounds and periodic replacement. Furthermore, these operations also depend on the net material. In this sense, it would be interesting to analyse how the management of nets made with alternative materials (e.g., copper nets) would vary and what their use could entail from an environmental performance point of view. For these reasons, an in-depth analysis of the impact due to infrastructure and equipment in sea bass and sea bream production should be performed.

Finally, regarding impact category, no studies investigated the water footprint (WF) of the production. As mentioned in the previous paragraph, in two studies, the impact category of water dependence was analysed. However, the Water Footprint Network and the ISO 14046 were not followed up in any study. The WF is an indicator that quantifies the virtual content of water in products or services (Lovarelli et al., 2016). In addition, according to Hoekstra et al. (2011), the WF is composed of three components: green water footprint, blue water footprint and grey water footprint. Since aquaculture is a sector that requires large volumes of water (i.e., freshwater, brackish water and saline water) and depends on its availability, an in-depth study of the water footprint of the production of sea bream and sea bass should be performed.

Regarding the LCA application, similar gaps were identified by previously carried out reviews focusing on the LCA application on aquaculture (Henriksson et al., 2012; Bohnes and Laurent, 2019; Bohnes et al 2018; Alameda et al., 2019) and salmon (Phillis et al., 2019). In detail:

- The role of LCA practitioners is still relevant because there is a wide heterogeneity of choices regarding all the first three steps of LCA,
- Quality of the data is often not homogeneous, and its effect on the environmental results is not always properly investigated with sensitivity and uncertainty analysis,
- Some of the environmental impacts related to aquaculture are only rarely investigated (e.g., impact on biodiversity (Blanchard et al., 2017), release of microplastics (Vazquez-Rowe et al., 2021; Zhou et al 2021), etc.),
- Most of the LCA studies focus on specific aquaculture farms. Despite this, the upscalability of the achieved results is not always discussed and addressed making the LCA outcomes less usable,

- The development of policies based on the results of the LCA studies is still a critical point. Despite most of the LCA outcomes could be useful to identify more sustainable/less impacting aquaculture rearing systems.

6. Future perspectives

Given the continuous growth of the sector and the increasing importance of seabass and seabream in Mediterranean aquaculture, an in-depth analysis of its environmental sustainability has become a prerogative and a preliminary step towards the designing of production processes with lower impacts. For this purpose, LCA is one of the most accepted and applied approaches. However, there are some limitations:

- Geographical representativity: given the volume of production, the economic importance and the growing aquaculture sector, more applications of LCA are needed to achieve a representative environmental “picture” of the current situation to assess how the innovations can affect the environmental performance; in addition, Turkish production, which represents about 50% of the Mediterranean production, should be analysed in order to have a representative figure about the environmental impact of this aquaculture sector.
- Standardisation of the choice of the functional unit: first, the choice of the FU should be standardised among the different studies and, in this regard, an energy-based or protein content-based FU should be used to facilitate comparison among the different studies and the different fish species.
- Increasing the transparency regarding the assumptions and choices made about some methodological and modelling approaches, such as system boundary definition. More details should be reported regarding the processes included or excluded, the type and source of the inventory data (e.g., if the data are primary or secondary data and if they are collected from the literature or databases), the

modelling approach used to estimate nutrient emissions as well as the use of infrastructure and equipment.

- Deepening the evaluation of infrastructure, equipment and fry, using primary data and providing all the necessary information.
- Expanding the sustainability analysis with assessments also of economic (LCC) and social (SLCA) sustainability and with an energy analysis to achieve a holistic sustainability assessment and avoid trade-off among the different sustainability levels/pillars.

Despite some research efforts were and are dedicated to the development of guidelines for LCA application to aquaculture, it is not possible to provide generalized guidelines for LCA of seabream and seabass aquaculture farms because the choices in term of system boundary and modelling (e.g., solving of multifunctionality, emission estimation) are deeply affected by the goal of the study. Despite this, if the goal of the LCA study doesn't focuses on capital goods (e.g., comparison between different type of sea cages), this input could be modelled using secondary data while most of the effort during the LCI should focus on the collection of primary data about feed composition and consumption and on the measurement of N and P emissions or their estimation using of specific models.

7. Conclusions

This review analysed the recent literature regarding LCA application to seabass and seabream production in the Mediterranean Sea. Although few studies have been performed so far, there is a great variability in the definition of the system boundaries, inventories and analysed impact categories. Feed is the main hotspot for most of the impact categories, and FCR is the key parameter to improve environmental performance. A better estimation of the feed efficiency should also consider nutrient efficiency and, thus,

the nutritional properties of the feed. Moreover, there is a lack of transparency of the data and information, which makes it difficult to interpret the results and compromises the reproducibility of the studies. No studies have analysed the application of mitigation strategies, although it is often reported that the use of alternative protein sources in fish meal and fish oil replacements can be a possible solution to increase sustainability.

It is therefore necessary to continue and deepen the application of the LCA methodology to this sector, especially for the validation of the mitigation strategies applied over the entire life cycle. Finally, for an overall sustainability assessment, from a life cycle perspective, further studies will also be required for an economic (LCC) and social (SLCA) evaluation and, to optimise the system, energy analysis should be performed.

Acknowledgements

This study was conducted within the framework of PRIMA S2 2018 project SIMTAP. SIMTAP "Self-sufficient Integrated Multi-Trophic AquaPonic systems for improving food production sustainability and brackish water use and recycling" (<https://www.simtap.eu/>) is part of the PRIMA Programme supported by the European Union.

References

- Ababouch, L., Fipi, F., & Carolu, C. (2015). Fisheries and Aquaculture in the Context of Blue Economy.http://www.un.org/disabilities/documents/rio20_outcome_document_complete.pdf.
- Abdou, K., Aubin, J., Romdhane, M. S., le Loc'h, F., & Lasram, F. B. R. (2017). Environmental assessment of seabass (*Dicentrarchus labrax*) and seabream (*Sparus aurata*) farming from a life cycle perspective: A case study of a Tunisian aquaculture farm. *Aquaculture*, 471, 204–212. <https://doi.org/10.1016/j.aquaculture.2017.01.019>.

- Abdou, K., ben Rais Lasram, F., Romdhane, M. S., le Loc'h, F., & Aubin, J. (2018). Rearing performances and environmental assessment of sea cage farming in Tunisia using life cycle assessment (LCA) combined with PCA and HCPC. *International Journal of Life Cycle Assessment*, 23(5), 1049–1062. <https://doi.org/10.1007/s11367-017-1339-2>.
- AgriBalyse. (2017). AgriBalyse life cycle inventory (LCI). ADEME. <https://nexus.openlca.org/database/Agribalyse>.
- Almeida, C., Loubet, P., da Costa, T. P., Quinteiro, P., Laso, J., Baptista de Sousa, D., ... & Marques, A. (2022). Packaging environmental impact on seafood supply chains: A review of life cycle assessment studies. *Journal of Industrial Ecology*, 26(6), 1961-1978.
- Aubin, J. (2013). Life Cycle Assessment as applied to environmental choices regarding farmed or wild-caught fish. In *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* (Vol. 8). <https://doi.org/10.1079/PAVSNNR2013011>.
- Aubin, J., Papatryphon, E., van der Werf, H. M. G., & Chatzifotis, S. (2009). Assessment of the environmental impact of carnivorous finfish production systems using life cycle assessment. *Journal of Cleaner Production*, 17(3), 354–361. <https://doi.org/10.1016/j.jclepro.2008.08.008>.
- Bartek, L., Strid, I., Hennrich, K., Junne, S., Rasi, S., & Eriksson, M. (2021). Life cycle assessment of fish oil substitute produced by microalgae using food waste. *Sustainable Production and Consumption*, 27, 2002–2021. <https://doi.org/10.1016/j.spc.2021.04.033>.
- Basto-Silva, C., Guerreiro, I., Oliva-Teles, A., & Neto, B. (2019). Life cycle assessment of diets for gilthead seabream (*Sparus aurata*) with different protein/carbohydrate ratios and fishmeal or plant feedstuffs as main protein sources. *International Journal of Life Cycle Assessment*, 24(11), 2023–2034. <https://doi.org/10.1007/s11367-019-01625-7>.
- Besson, M., de Boer, I. J. M., Vandeputte, M., van Arendonk, J. A. M., Quillet, E., Komen, H., & Aubin, J. (2017). Effect of production quotas on economic and environmental values

- of growth rate and feed efficiency in sea cage fish farming. *PLoS ONE*, 12(3).
<https://doi.org/10.1371/journal.pone.0173131>.
- Biermann, G., & Geist, J. (2019). Life cycle assessment of common carp (*Cyprinus carpio* L.)–
A comparison of the environmental impacts of conventional and organic carp
aquaculture in Germany. *Aquaculture*, 501, 404-415.
- Blanchard, J. L., Watson, R. A., Fulton, E. A., Cottrell, R. S., Nash, K. L., Bryndum-Buchholz, A.,
... & Jennings, S. (2017). Linked sustainability challenges and trade-offs among fisheries,
aquaculture and agriculture. *Nature ecology & evolution*, 1(9), 1240-1249.
- Bohnes, F. A., & Laurent, A. (2019). LCA of aquaculture systems: methodological issues and
potential improvements. In *International Journal of Life Cycle Assessment* (Vol. 24, Issue
2, pp. 324–337). Springer Verlag. <https://doi.org/10.1007/s11367-018-1517>.
- Bohnes, F. A., Hauschild, M. Z., Schlundt, J., & Laurent, A. (2018). Life cycle assessments of
aquaculture systems: a critical review of reported findings with recommendations for
policy and system development. <https://doi.org/10.1111/raq.12280>.
- Bordignon, F., Sturaro, E., Trocino, A., Birolo, M., Xiccato, G., & Berton, M. (2022).
Comparative life cycle assessment of rainbow trout (*Oncorhynchus mykiss*) farming at
two stocking densities in a low-tech aquaponic system. *Aquaculture*, 556, 738264.
- Bordignon, F., Trocino, A., Sturaro, E., Martínez-Llorens, S., Tomas-Vidal, A., Xiccato, G., &
Berton, M. (2023). Fish oil substitution with vegetable oils in diets for greater amberjack
(*Seriola dumerili*): A consequential life cycle assessment approach. *Aquaculture*, 563,
738903.
- Børresen, T., (2013). Blue growth opportunities in sustainable marine and maritime sectors.
Journal of Aquatic Food Product Technology, 22 (3), 217-218.
<https://doi.org/10.1080/10498850.2013.783748>.

- Cao, L., Diana, J. S., & Keoleian, G. A. (2013). Role of life cycle assessment in sustainable aquaculture. *Reviews in Aquaculture*, 5(2), 61–71. doi.org/10.1111/j.1753-5131.2012.01080.
- Cardia, F. & Lovatelli, A. (2015). Aquaculture operations in floating HDPE cages: a field handbook. FAO Fisheries and Aquaculture Technical Paper No. 593. Rome, FAO. 152 pp.
- Cho, C. Y., & Kaushik, S. J. (1990). Nutritional energetics in fish: energy and protein utilization in rainbow trout (*Salmo gairdneri*). *Aspects of food production, consumption and energy values*, 61, 132-172.
- Conceição, L. E., Yúfera, M., Makridis, P., Morais, S., & Dinis, M. T. (2010). Live feeds for early stages of fish rearing. *Aquaculture research*, 41(5), 613-640. doi:10.1111/j.1365-2109.2009.02242.x
- Consultants, B. (2014). Agri-footprint - LCA food database. <http://www.agri-footprint.com>.
- Cooney, R., Tahar, A., Kennedy, A., & Clifton, E. (2021). The dilemma of opportunity in developing a life cycle assessment of emerging aquaculture systems—a case study of a Eurasian perch (*Perca fluviatilis*) hatchery recirculating aquaculture system. *Aquaculture*, 536, 736403.
- Costantini, M., Ferrante, V., Guccino, M., & Bacenetti, J. (2021). Environmental sustainability assessment of poultry productions through life cycle approaches: A critical review. *Trends in Food Science & Technology*, 110, 201-212. <https://dx.doi.org/10.1016/j.tifs.2021.01.086>.
- d'Orbcastel, E. R., Blancheton, J. P., & Aubin, J. (2009). Towards environmentally sustainable aquaculture: Comparison between two trout farming systems using Life Cycle Assessment. *Aquacultural Engineering*, 40(3), 113–119. <https://doi.org/10.1016/j.aquaeng.2008.12.002>.
- Ellingsen, H., & Aanonsen, S. A. (2006). Environmental impacts of wild caught cod and farmed Salmon—a comparison with chicken (7 pp). *The International Journal of Life Cycle Assessment*, 11(1), 60-65. <https://doi.org/10.1065/lca2006.01.236>.

- European Commission. (2019). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal. Communication no. COM/2019/640. Brussels: European Commission. Accessed at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:640:FIN>.
- European Commission. (2020). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system COM/2020/381 final.
- European Commission. (2021). European Green Deal: Commission Adopts Strategic Guidelines for Sustainable and Competitive EU Aquaculture.
- FAO. (2020). The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome. doi.org/10.4060/ca9229en.
- FAO. (2022). The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. Rome, FAO. [http://doi.org/10.4060/cc0461en](https://doi.org/10.4060/cc0461en).
- FishStatJ. (2022). FAO - FAO Fishery and Aquaculture Global Statistics. <https://www.fao.org/fishery/en/statistics>.
- Fraga-Corral, M., Ronza, P., Garcia-Oliveira, P., Pereira, A. G., Losada, A. P., Prieto, M. A., ... & Simal-Gandara, J. (2022). Aquaculture as a circular bio-economy model with Galicia as a study case: How to transform waste into revalorized by-products. *Trends in Food Science & Technology*, 119, 23-35.
- Fry, J. P., Mailloux, N. A., Love, D. C., Milli, M. C., & Cao, L. (2018). Feed conversion efficiency in aquaculture: do we measure it correctly?. *Environmental Research Letters*, 13(2), 024017. <https://doi.org/10.1088/1748-9326/aaa273>.

- Garcia, B. G., Jiménez, C. R., Aguado-Giménez, F., & Garcia, J. G. (2016). Life cycle assessment of gilthead seabream (*Sparus aurata*) production in offshore fish farms. *Sustainability (Switzerland)*, 8(12). <https://doi.org/10.3390/su8121228>.
- Garcia, B. G., Jiménez, C. R., Aguado-Giménez, F., & Garcia, J. G. (2019). Life cycle assessment of seabass (*Dicentrarchus labrax*) produced in offshore fish farms: Variability and multiple regression analysis. *Sustainability (Switzerland)*, 11(13). <https://doi.org/10.3390/su11133523>.
- Glencross, B. D., Huyben, D., & Schrama, J. W. (2020). The Application of Single-Cell Ingredients in Aquaculture Feeds-A Review. *Fishes*, 5.3:22. <https://doi.org/10.3390/fishes5030022>.
- Guinée, J. B. (Ed.). (2002). Handbook on life cycle assessment: operational guide to the ISO standards (Vol. 7). Springer Science & Business Media. <https://doi.org/10.1007/BF02978897>.
- Henriksson, P. J. G., Guinée, J. B., Kleijn, R., & de Snoo, G. R. (2012). Life cycle assessment of aquaculture systems-A review of methodologies. In *International Journal of Life Cycle Assessment* (Vol. 17, Issue 3, pp. 304–313). <https://doi.org/10.1007/s11367-011-0369-4>.
- Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., (2011). The Water Footprint Assessment Manual (February 2011, <http://doi.org/978-1-84971-279-8>).
- ISO 14040 (2006). Environmental management — Life cycle assessment — Requirements and guidelines. International Organization for Standardization.
- ISO 14044 (2018). Environmental management — Life cycle assessment — Principles and framework. International Organization for Standardization.
- ISO 14046 (2014). Environmental Management — Water Footprint — Principles, Requirements and Guidelines.

- Jerbi, M. A., Aubin, J., Garnaoui, K., Achour, L., & Kacem, A. (2012). Life cycle assessment (LCA) of two rearing techniques of sea bass (*Dicentrarchus labrax*). *Aquacultural Engineering*, 46(1), 1–9. <https://doi.org/10.1016/j.aquaeng.2011.10.001>.
- Kallitsis, E., Korre, A., Mousamas, D., & Avramidis, P. (2020). Environmental life cycle assessment of mediterranean sea bass and sea bream. *Sustainability (Switzerland)*, 12(22), 1–11. <https://doi.org/10.3390/su12229617>.
- Konstantinidis, E., Perdikaris, C., & Ganias, K. (2021a). Life cycle assessment of seabass and meagre in marine cage farming - From feeding plant to harvesting. *Mediterranean Marine Science*, 22(1), 125–136. <https://doi.org/10.12681/mms.25052>.
- Konstantinidis, E., Perdikaris, C., & Ganias, K. (2021b). Life cycle assessment during packaging of market-sized seabass and meagre: necessary adaptations toward GHG neutrality. *International Journal of Life Cycle Assessment*, 26(7), 1456–1470. <https://doi.org/10.1007/s11367-021-01743-9>.
- Konstantinidis, E., Perdikaris, C., Gouva, E., Nathanielides, C., Bartzanas, T., Anestis, V., Ribaj, S., Tzora, A., & Skoufos, I. (2020). Assessing Environmental Impacts of Sea Bass Cage Farms in Greece and Albania Using Life Cycle Assessment. *International Journal of Environmental Research*, 14(c), 693–704. <https://doi.org/10.1007/s41742-020-00289-8>.
- Le Féon, S. le, Dubois, T., Jheer, C., Wilfart, A., Akkal-Corfini, N., Bacenetti, J., Costantini, M., & Aubin, J. (2021). De(aqua, a model to assess the sustainability of aquaculture systems: Methodological development and application to a french salmon farm. *Sustainability (Switzerland)*, 13(14). <https://doi.org/10.3390/su13147779>.
- Lovarelli, D., Bacenetti, J., & Fiala, M. (2016). Water Footprint of crop productions: A review. *Science of the Total Environment*, 548, 236–251. <https://doi.org/10.1016/j.scitotenv.2016.01.022>.

- Lovarelli, D., Ingraio, C., Fiala, M., & Bacenetti, J. (2018). Beyond the Water Footprint: A new framework proposal to assess freshwater environmental impact and consumption. *Journal of Cleaner production*, 172, 4189-4199.
- Maiolo, S., Parisi, G., Biondi, N., Lunelli, F., Tibaldi, E., & Pastres, R. (2020). Fishmeal partial substitution within aquafeed formulations: Life cycle assessment of four alternative protein sources. *The International Journal of Life Cycle Assessment*, 25(8), 1455-1471. <https://doi.org/10.1007/s11367-020-01759-z>.
- Marvin, H. J., van Asselt, E., Kleter, G., Meijer, N., Lorentzen, G., Johansen, L. H., ... & Mendoza Beltran, A., Chiantore, M., Pecorino, D., Corner, R. A., Ferreira, J. G., Cò, R., Fanciulli, L., & Guinée, J. B. (2018). Accounting for inventory data and methodological choice uncertainty in a comparative life cycle assessment: the case of integrated multi-trophic aquaculture in an offshore Mediterranean enterprise. *International Journal of Life Cycle Assessment*, 23(5), 1063–1077. <http://doi.org/10.1007/s11367-017-1363-2>.
- Moreno Ruiz, E., Lérová, T., Reinhard, J., Valsasina, L., Bourgault, G., Wernet, G., (2016). Documentation of Changes Implemented in Ecoinvent Database v3. 3. Ecoinvent, Zürich, Switzerland.
- Notarnicola, B., Salomone, R., Fotti, L., Renzulli, P. A., Roma, R., & Cerutti, A. K. (2015). Life cycle assessment in the agri-food sector. *Life cycle assessment in the agri-food sector: system studies, methodological issues and best practices*, 10-68.
- Pahri, S. D. R., Mohamed, A. F., & Samat, A. (2015). LCA for open systems: a review of the influence of natural and anthropogenic factors on aquaculture systems. In *International Journal of Life Cycle Assessment* (Vol. 20, Issue 9, pp. 1324–1337). Springer Verlag. <https://doi.org/10.1007/s11367-015-0929-0>.
- Papatryphon, E., Petit, J., Kaushik, S. J., & van der Werf, H. M. (2004). Environmental impact assessment of salmonid feeds using life cycle assessment (LCA). *AMBIO: A Journal of the Human Environment*, 33(6), 316-323. <https://doi.org/10.1579/0044-7447-33.6.316>

- Philis, G., Ziegler, F., Gansel, L. C., Jansen, M. D., Gracey, E. O., & Stene, A. (2019). Comparing life cycle assessment (LCA) of salmonid aquaculture production systems: status and perspectives. *Sustainability*, 11(9), 2517.
- Pré Consultant, (2004). The BUWAL 250 Library, SimaPro Database Manual. Pré Consultant, The Netherlands, 37p.
- Rosa, J., Lemos, M. F., Crespo, D., Nunes, M., Freitas, A., Ramos, F., ... & Leston, S. (2020). Integrated multitrophic aquaculture systems–Potential risks for food safety. *Trends in Food Science & Technology*, 96, 79-90.
- Sala, S., Anton, A., McLaren, S. J., Notarnicola, B., Saouter, F., & Sonesson, U. (2017). In quest of reducing the environmental impacts of food production and consumption. *Journal of Cleaner Production*, 140, 387–398. <https://doi.org/10.1016/J.JCLEPRO.2016.09.054>.
- Samuel-Fitwi, B., Wuertz, S., Schroeder, J. P., & Schulz, C. (2012). Sustainability assessment tools to support aquaculture development. *Journal of Cleaner Production*, 32, 183-192. <http://dx.doi.org/10.1016/j.jclepro.2012.03.037>.
- Scarborough, P., Appleby, P. N., Mizdrak, A., Briggs, A. D., Travis, R. C., Bradbury, K. E., & Key, T. J. (2014). Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. *Climatic change*, 125(2), 179-192. <https://doi.org/10.1007/s10584-014-1169-1>.
- Schade, S., Stangl, G. I., & Meier, T. (2020). Distinct microalgae species for food-part 2: comparative life cycle assessment of microalgae and fish for eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA), and protein. <https://doi.org/10.1007/s10811-020-02181-6>.
- Silva, C. B., Valente, L. M., Matos, E., Brandão, M., & Neto, B. (2018). Life cycle assessment of aquafeed ingredients. *The International Journal of Life Cycle Assessment*, 23(5), 995-1017. <https://doi.org/10.1007/s11367-017-1414-8>.

- Silvenius, F., Grönroos, J., Kankainen, M., Kurppa, S., Mäkinen, T., & Vielma, J. (2017). Impact of feed raw material to climate and eutrophication impacts of Finnish rainbow trout farming and comparisons on climate impact and eutrophication between farmed and wild fish. *Journal of Cleaner Production*, 164, 1467-1473. <https://doi.org/10.1016/j.jclepro.2017.07.069>.
- Sonesson, U., Davis, J., Flysjö, A., Gustavsson, J., & Witthöft, C. (2017). Protein quality as functional unit – A methodological framework for inclusion in life cycle assessment of food. *Journal of Cleaner Production*, 140, 470–478. <https://doi.org/10.1016/J.JCLEPRO.2016.06.115>.
- Vázquez-Rowe, I., Ita-Nagy, D., & Kahhat, R. (2021). Microplastics in fisheries and aquaculture: Implications to food sustainability and safety. *Current Opinion in Green and Sustainable Chemistry*, 29, 100464.
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): Overview and methodology. *International Journal of Life Cycle Assessment*, 21(9), 1213–1230.
- Zhou, A., Zhang, Y., Xie, S., Chen, Y., Li, X., Wang, J., & Zou, J. (2021). Microplastics and their potential effects on the aquaculture systems: A critical review. *Reviews in Aquaculture*, 13(1), 719-733.
- Ziegler, F., Hornborg, S., Green, B. S., Eigaard, O. R., Farmery, A. K., Hammar, L., ... & Smith, A. D. (2016). Expanding the concept of sustainable seafood using Life Cycle Assessment. *Fish and Fisheries*, 17(4), 1073-1093. <https://doi.org/10.1111/faf.12159>.

Author Contributions: Conceptualization, M.Z., and J.B.; methodology, M.Z., and J.B.; writing— original draft preparation, M.Z.; writing—review and editing, M.Z., L.R., C.B., and J.B.; funding acquisition, J.B and C.B.; and supervision, J.B and C.B.

All authors have read and agreed to the published version of the manuscript.

Journal Pre-proof

Declaration of interests

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

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

On behalf of all the Authors

Josef Beneš

Journal Pre-proof

1. Seabream and seabass production has grown steadily over the last decades
2. LCA studies about seabass and seabream farming in the Mediterranean area were reviewed
3. Mass-based functional unit and from-cradle-to-farm-gate boundaries were always selected
4. There is lack of transparency regarding inventory data and processes included in the boundary
5. Feed Conversion Ratio is the parameter most influencing the environmental performance

Journal Pre-proof