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Quantification and characterization of the environmental impact of sea bream and sea bass production in Italy

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ABSTRACT

While the production of fish from aquaculture has grown steadily over the years worldwide, some environmental concerns have emerged. In this study, the environmental impacts and main hotspots of a typical Italian sea bass and sea bream offshore farm were analysed. The Life Cycle Assessment (LCA) methodology was applied with a "cradle to farm gate" perspective and 1 ton of fish at harvest size as the functional unit. The results confirm that feed is the main hotspot and contributes across impact categories always at least 60%, with the exception of marine eutrophication driven instead by nutrient emissions. In some impact categories, infrastructure and farm operations also have a relevant impact (about 30%). The impacts of this case study are slightly lower than those found in the literature, and this is mainly due to prior attention of the company to feed formulation. An alternative scenario was also explored, by reducing the amount of uningested feed, showing a reduction in the Global Warming Potential by 6% and in marine eutrophication by up to 10%. The application and evaluation of new technologies (e.g., automated feed dispenser, use of alternative cage materials) could be explored in future research.

1. Introduction

Aquaculture has grown strongly in recent years. Since the 2000s there has been a progressive increase in aquaculture production, while capture production has remained stable. Currently the productions from aquaculture have reached 87.5 million tons against the 90.3 million tons of fisheries on a global scale (FAO, 2022). One of the main drivers of aquaculture production is the global demand for fish which increased from 14.3 kg per-capita in 1990s to 20.2 kg per capita in 2020 (FAO, 2022). In Europe, fish production is around 5.0 million tons, of which 1.1 million tons from aquaculture and 3.9 million tons from captures (EUOMOFA, 2022). The European per-capita consumption is 23.3 kg, of which only the 27.9% (6.5 kg) comes from aquaculture (EUOMOFA, 2022). However, focusing on specific species, such as of Gilthead sea bream (*Sparus aurata,* GSB) and European sea bass (*Dicentrarchus labrax*, ESB), the consumption of farmed fish is higher than captured. During 2020 the average per-capita consumption of GSB in EU was 0.29 kg of which 0.28 kg (96.6%) from aquaculture, while ESB per-capita consumption was 0.22 kg of which 0.21 kg (95.5%) from aquaculture (EUOMOFA, 2022). These two species are the most farmed in the Mediterranean basin and Italy as well, among marine water species. The ever-increasing productions of GSB and ESB in Italy led to a progressive change in farming techniques. In fact, since 1990s the production of marine aquaculture species has passed from traditional "in-land" systems (flow-through and extensive systems such as "vallicoltura") to coastal and off-shore farms (Parisi et al., 2014). Currently Italian production of both species has reached 7500 and 9600 tons for ESB and GSB, respectively (API, 2022).

With the increase in aquaculture production, some environmental concerns have emerged over the years. Therefore, in recent years there has been a strong focus from the scientific community and industry to investigate more sustainable solutions to support the growth of the sector. The greatest environmental concerns are related with the use of natural resources on a global scale mainly for feed production (Abdou et al., 2017). Moreover, several local phenomena such as the release of nutrients in the water, the bio deposition of organic compounds from

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fish farms into the benthic environment, the transmission of diseases, the dispersion of non-native species, and the release of antibiotics and pharmaceuticals into the water can be highlighted (Abdou et al., 2017; Aubin, 2013; Cao et al., 2013). Several strategies can be applied to reduce the environmental impact of aquaculture, such as the use of alternative ingredients in feed, a more efficient management and formulation of feeds, or the application of integrated farming techniques that reduce the environmental impact of fish farms by the direct or indirect assimilation of nutrients by low-trophic organisms, also called extractive (Bohnes et al., 2019; Nederlof et al., 2022). An example of this is the Integrated Multitrophic Aquaculture (IMTA) which allows for a substantial reduction of the nitrogen, phosphorus, and carbon load from aquaculture facilities in the environment by 50%, 40% and 40–50%, respectively (Nederlof et al., 2022). However, the investigation of the environmental impact of this sector and the evaluation of the mitigation strategies requires more attention and further research.

The application of the Life Cycle Assessment (LCA) methodology allows to evaluate the environmental impact of a process/product with a holistic approach and to quantify specific emissions. Thus, the whole life cycle of a product/process is analysed with the aim of identifying the characterizing phases that contribute mostly to the environmental impact (hotspots). Furthermore, the LCA methodology makes it possible to evaluate a broad spectrum of environmental effects and to consequently avoid the phenomenon of environmental burden shifting which occurs when few environmental impacting elements are considered (Bohnes et al., 2019). LCA is widely used in the agricultural production sector and has recently been widely applied to the aquaculture sector as well (Aubin 2013; Bohnes et al., 2019). In particular, the LCA has been applied for the analysis of case studies (Abdou et al., 2017), to compare species or production systems (Aubin et al., 2009; Chary et al., 2020; Martini et al., 2022; Håland Gaeta et al., 2022) or it can be applied to some specific phases of the life cycle of aquaculture products such as the production of feed or the comparison of innovative ingredients (Basto-Silva et al., 2018, 2019; Maiolo et al., 2020). Regarding the production of GSB and ESB in Italy only one case study is present in the scientific literature (Mendoza Beltran et al., 2018). However, given the growing importance of the sector further applications and studies are needed to deepen the topic and to expand the knowledge about the impact of these farming systems. In this regard, the aim of this study is to quantify and characterize the environmental impact of a large ESB and GSB farm with a classic offshore production system. The LCA methodology was applied to this case study, which is representative of the Italian context given the large annual production of the analysed farm, equal to about 10% of the national production of these two species.

2. Materials and methods

2.1. Goal and scope definition

The goal of this study is to assess the environmental performances related to the production of GSB and ESB in an offshore aquaculture facility in the Tyrrhenian Sea, to quantify the potential environmental impact and identify the most impactful processes (hotspots) within the entire production process. Moreover, the reduction of non-ingested feed was evaluated in an alternative scenario (AS), compared to reference values of the baseline scenario (BS). This allowed an analysis of the environmental benefits that a reduction of feed wastage (i.e., avoided uningested feed) could provide.

The results of this study could help aquaculture stakeholders assess the environmental sustainability of their production processes and guide the application of future mitigation strategies.

2.2. Description of the offshore production system

The analysis was performed in a company specialized in the production of GSB and ESB in central Italy (Tyrrhenian Sea, Gulf of Follonica - N: 42° 50′ 22’’; E: 10° 37′ 46″). The off-shore rearing facility consists of floating cages (30m in diameter and 15m deep) located 4 nautical miles from the coastline. The cycle begins by using juveniles weighing 3 g on average that are reared up to 400–600 g. The total annual production is about 1800 tonnes, equally divided between GSB and ESB. The economic feed conversion ratio (FCR = kg of distributed feed/kg of live fish weight produced, Aubin et al., 2009) in the reference year was 2.4 and 1.9 for ESB and GSB, respectively. The entire production process can be divided into several subsystems for LCA analysis: (I) manufacturing, maintenance, and disposal of infrastructure (floating cages, nets, and other equipment); (II) fry production; (III) feed production; and (IV) fish production and rearing. The first step consists in the assembly of floating collar cages and mooring system that usually take place directly on site. The lifetime of cages is usually 10 years, while that of nets and ropes is shorter. The periodical maintenance consists in the substitutions of nets or to replace damaged components (i.e., after adverse sea conditions). Another routinary maintenance conducted at the farm level is the cleaning of the rearing nets. The production of fry take place in specific farms (hatcheries), often located in-land with highly technological systems such as recirculating aquaculture systems (RAS). Hatcheries use specific protocol for the reproduction of broodstock and the weaning of larvae, that change according to the target species (Shields, 2001; Conceição et al., 2010). Feeds are usually formulated according to the nutrient requirement of a specific species and life-stage of fish. In carnivorous fish feed such as GSB and ESB extruded feed are usually used in the on-growing stage with a crude protein content of 35–60% and lipid content of 9–26%, according to the life stage (Teles et al., 2011; Kousoulaki et al., 2015). In recent years the reduction of ingredients of aquatic origin (i.e., fishmeal and fish oil) has gathered great attention in the scientific community and aquaculture industry (Aragão et al., 2020). The production of fish includes all rearing, feeding, and catching operations. A detailed guide for operation in sea cages can be found in Cardia and Lovatelli (2015).

2.3. Functional unit

The functional unit (FU) represents the reference unit to which all environmental impacts are related. According to ISO 14040 (ISO, 2006) FU must be measurable and best represent the function of the production process. Thus, since the aim of the present study is to evaluate the impact of fish production at the farm gate, 1 ton of fish biomass (whole body) at the harvest size was selected as FU.

In particular, since the primary data collected allowed for the calculation of separate impacts for GSB and ESB, the following FUs were selected:

- 1 ton of ESB at the harvest size;
- 1 ton of GSB at the harvest size;
- 1 ton of average fish at the harvest size.

The mass-based FU has been used in most previous LCA studies concerning GSB and ESB production (Aubin et al., 2009; Abdou et al., 2017; Jerbi et al., 2012) and it provides a good basis for comparison with previous studies. However, in a study evaluating the environmental impact of a food item, comparability may be weakened by the fact that a mass-based FU does not express food functionality (McLaren et al., 2021). Therefore, in this study the analysis was also carried out by choosing 100 kcal and 1 kg protein as FU (results shown in supplementary materials).

2.4. System boundary

The system boundaries define the theoretical boundaries of an LCA study and are necessary to specify which phases of the life cycle of the analysed product are included in the analysis. In this study, a " cradle to gate” approach was adopted considering all the operations from the extraction of raw materials to the harvesting of fish (Fig. 1). In particular, the following sub-processes were considered: i) extraction and production of raw materials and energy input (e.g., minerals, fossil resources, lubricant oil); manufacturing, maintenance, and disposal of infrastructure (e.g. floating collar cages, nets, mooring systems); iii) juveniles production and supply; iv) feed production and supply (e.g., agricultural processes for plant based ingredient, wild fisheries for marine based protein, transport); iv) farm management (feed distribution, fish monitoring and harvest); v) emissions related to fuels combustion; vi) emissions related to fish metabolism (nitrogen and phosphorus compounds).

Post-harvest processes (such as processing, packaging, consumption and end-of-life) were excluded from the analysis since they are not directly dependent on the company. However, in the future, for a complete life cycle perspective, the analysis should be extended to include post-harvest processes as well.

2.5. *Inventory data collection*

The life cycle inventory (LCI) consists in the collection of data needed for the analysis. Two different types of inventory data were used: primary data, directly provided by the company, and secondary data, obtained from databases, literature or estimated using specific models.

The information regarding the 2021 annual production has been provided by the company. For the nutritional composition of the feed and the quantities administered, primary data were used in the analysis. In particular, the company provided specific guidance for the amount of feed administrated to both species. In this way, it was possible to precisely differentiate the specific FCR of ESB and GSB. For the processing of raw materials included in the feed at the feed factory, primary data were not available, thus average data from the literature were used (Nemecek and Kägi, 2007). The inclusion of the different ingredients, which differ between the different stages of growth of the fish, was estimated and balanced on the basis of the proximate composition of the feed and fixed inclusion of ingredients of aquatic origin (i.e., fishmeal, fish oil, and krill meal), specified by the manufacturer. The International Aquaculture Feed Formulation Database (IAFFD) was used as reference for the formulation of feed used in the farm. Primary data were also used for the number of juveniles introduced and for energy consumption (i.e., electricity and fuels).

For the modelling of the floating collar cages and the entire mooring system, a mix of primary data provided by the company and data by Olivares (2003) was used.

A nutrient mass-balance model (adapted from Cho, 2004) was used for the estimation of the Nitrogen and Phosphorous released into the water associated with fish metabolism. Emissions were estimated for each species raised. In particular, solid and dissolved N and P were calculated on the basis of the difference between the quantities of nutrients supplied to the fish through feed and the quantities assimilated during growth. A simple mass balance approach was considered to calculate the amount of solid (SW) and dissolved (DW) waste produced by fish metabolism during the period. The model considers the following equations:

1. $TW = SW + DW$

where TW are the total wastes produced by fish, SW are the solid wastes, and DW the dissolved wastes.

SW and DW were calculated as follow:

2. $SW = FW + NIF$

where FW is the faecal waste and NIF is the not ingested feed. FW were calculated as follow:

3. $FW = (FI - NIF) \times (1 - ADC)$

where FI is the N and P content in the feed intake and ADC is the apparent digestibility coefficient of a specific nutrient (e.g., N and P). The ADC coefficient is specie- and feed-specific. Reference values of ADC and NIF were derived from literature (Ballester-Moltó et al., 2017a; 2017b).

4. $DW = [(FI - NIF) \times ADC] - [FP - (FS + FM)]$

where FP is the N and P content in fish produced, FS is the N and P content in the fish stock biomass and FM is the N and P content in dead fish. The whole-body composition of both species was derived from specific scientific literature (Lupatsch and Kissil, 1998; Aragão et al., 2020; Ballestrazzi et al., 1998). Nutrient balance modelling approach has previously been adapted for other LCA studies (Garcia Garcia et al., 2016; Abdou et al., 2017; Konstantinidis et al., 2020). Finally, the production of juveniles was modelled starting from data present in

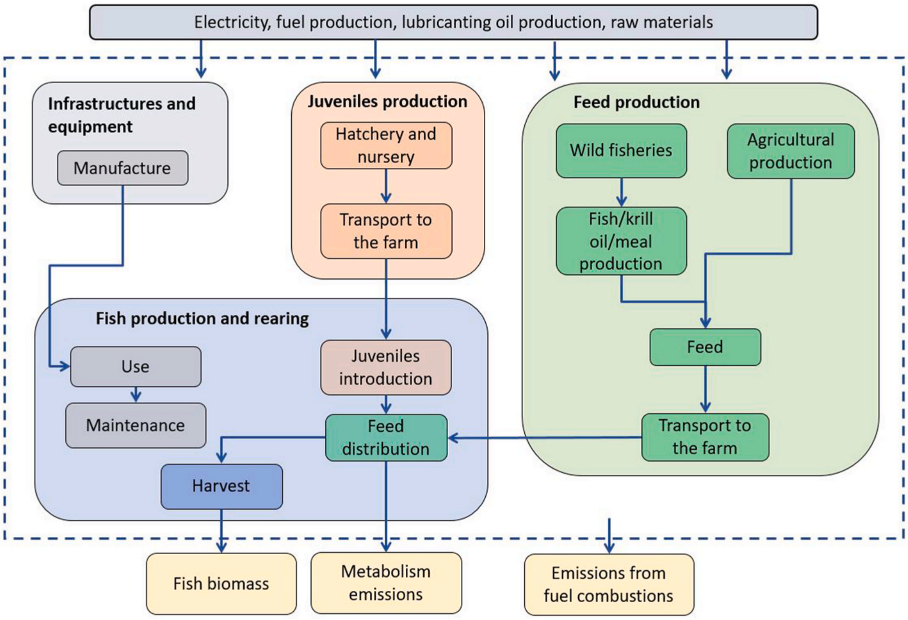

Fig. 1. Graphical representation of system boundaries and schematization of all subprocesses considered in the analysis.

literature (Garcia Garcia et al., 2019), considering their transport by land for a distance of 1000 km at a density in water of 50 kg/m^3 (Lekang, 2013). As for the infrastructures, these have been modelled starting from the datasets regarding the floating collar cages contained in Ecoinvent (Weidema et al., 2013). These were adapted to the context under analysis (e.g. by removing steel for cages catwalks, absent in this farm) based on farm survey and interviews with company staff. For nets and ropes, made of polyamide, 2 years lifespan have been considered; while for floating pipes, made of polyethylene, and chains and wire ropes, made of steel, 10 years.

Finally, for emissions from fuel combustion secondary data were also used.

Ecoinvent v3.8 (Weidema et al., 2013), Agri-footprint v6 (Blonk Agri-footprint, 2022), and Agribalyse v3 (AgriBalyse, 2017) databases were used for background data.

In Table 1 the most important inputs and outputs obtained from LCI are summarized.

2.6. Life cycle impact assessment (LCIA)

With the Recipe Midpoint (H) 2016 method, the environmental profile of the production process was evaluated, considering different impact categories: Global warming potential (GWP), ozone layer depletion (OD), ozone formation - human health (OF -hh), formation of fine particles (PM), ozone formation – terrestrial ecosystems (OF-te), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (Tex), ecotoxicity of freshwater (Fex), marine ecotoxicity (Mex), human carcinogenic toxicity (HT-c), human non-carcinogenic toxicity (HT-noc), mineral resource depletion (MRS), fossil resource depletion (FRS). This impact assessment method was chosen because it is currently considered the most up-to-date and robust in providing characterization factors that are representative for the global scale (Huijbregts et al., 2017). In the past CML-IA has been the most used method for the fish and seafood industry but recently it showed a marked decline in favor of the aforementioned Recipe (Ruiz-Salmon et al., 2021). For this reason, the latter is the one that most facilitates comparisons with the current literature. Knowing, however, that some impact categories have more local than global relevance, we also evaluated the inventory with the Environmental Footprint 3.0 method (Fazio et al., 2018), developed by the European Commission (CE) through the PEF initiative. The results are reported in the supplementary materials.

Moreover, total cumulative energy demand (TCED) and net primary production use (NPPU) were calculated. Total cumulative energy demand (TCED) represents the amount of energy (e.g., fossil fuels, wood, electricity) required for fish production, it is expressed in MJ and was calculated according to the lower heating values available in SimaPro® (PRé Consultants, 1997). NPPU represents the amount of carbon (C) necessary for fish production as a biotic resource, that it is consequently unavailable for other purposes, and is expressed in kg of C (Papatryphon et al., 2004). For ingredients of terrestrial origin, the C content of crops (g C per kg of crop dry matter) according to Tyedmers (2001) were used. For fishery-derived raw materials, the C content was derived from Pauly et Christensen, (1995). The analysis of the impact of the use of antibiotics was excluded, due to the lack of inventory information in this regard.

Table 1
Main inputs and outputs considered in the analysis for 1 ton of gilthead sea bream (GSB) and 1 ton of European sea bass (ESB) in the reference system.

Inputs	GSB	ESB	Outputs	GSB	ESB
Juveniles [#]	2667	3111	Fish [kg]	1000	1000
Feed[a] [kg]	1945.0	2377.2	Nitrogen [kg]	110.3	137.2
N [kg]	140.4	171.6	N dissolved [kg]	86.7	107.3
P [kg]	20.5	25.1	N solid [kg]	23.6	29.9
Electricity[b] [kWh/y]	12.8		Phosphorous [kg]	13.7	18.0
Fuel[b] [L/y]	55.6		P dissolved [kg]	5.5	3.5
Mortality rate [%]	8	20	P solid [kg]	8.1	14.4

[a] N and P concentration of 7.2 and 1.1%, respectively (weighed mean of different feed) according to IAFFD composition data of aquaculture feed ingredients.

[b] Primary data referred to the fish production and rearing stage.

3. Results

3.1. Contribution analysis

The contribution analysis (Fig. 2) allows to identify the contribution of the different sub-processes, production factors or emissions that characterize the analysed process, in relation to the total impact for each impact category. In this way, it is possible to identify the sub-processes or production factors that mostly contribute to the impact for each impact category.

The sub-process "farming management" includes fuel and oil consumption and combustion linked to both operations in the sea (i.e., feeding, fish management etc.) and on land, as well as energy consumption (electricity and gas). The sub-process "feed production and supply" includes the impact related with the production and transport of the various ingredients included in the feed used and their processing. The sub-process "infrastructure and equipment" considers the production and maintenance of cages and related structures and the manufacture of different kind of boats, considering lifespan. Finally, the sub-process "fry production and supply" considers the production of juveniles and their transportation over 1000 km to the farm.

Feed production is the most impacting process and, except for ME, shows an impact share of 61% for ozone formation and increasing up to 98.4% for NPPU.

Farm management impacts above all on the OF-hh and OF-te (29.8% and 29.4%, respectively) and on the formation of particulate matter (18.4%); this is mostly due to the high consumption of fuel for boats and terrestrial machinery. The infrastructures mainly affect the HCT (24.6%), MRS (10%). The emissions of N and P compounds related with metabolic activity of fish represent almost all the impact in ME (97.4%). On the contrary, the production and transport of juveniles has a limited impact in all impact categories (less than 6%).

In detail, the impact on GWP is due for 87.5% to the production and transportation of feed, for 3.6% to the infrastructures and equipment, for 6.7% to farm management operations and for 2.2% to fry production.

3.2. Environmental impact

In Table 2 the impacts per ton of ESB, GSB and the average of both species produced at the farm gate is showed. The analysis was performed by differentiating inputs and information concerning feed production and supply, fry production and supply, mortality rate for both species, while common inputs (infrastructure, boats, energy consumption, etc.), were allocated between the two species with a mass-based allocation.

Global warming potential is 3137, 2622 and 2901 kg CO_2 eq for sea bass, sea bream and average fish produced by the farm, respectively. In general, GSB has lower impacts than ESB in all impact categories, ranging from −12% for OF-hh and OF-te and −20% for ME. This is mainly due to the higher FCR of sea bass (2.4 for sea bass and 1.9 for sea bream), which also leads to higher emissions of nitrogen compounds per ton of fish produced, therefore a greater contribution to marine eutrophication. The latter is the impact category with the largest difference between the two species (−20%).

Finally, ESB has a higher average mortality rate than sea bream within the cycle (20 and 8% respectively), thus more juveniles are required to achieve the same production, and this is another factor that determines the higher impact in ESB.

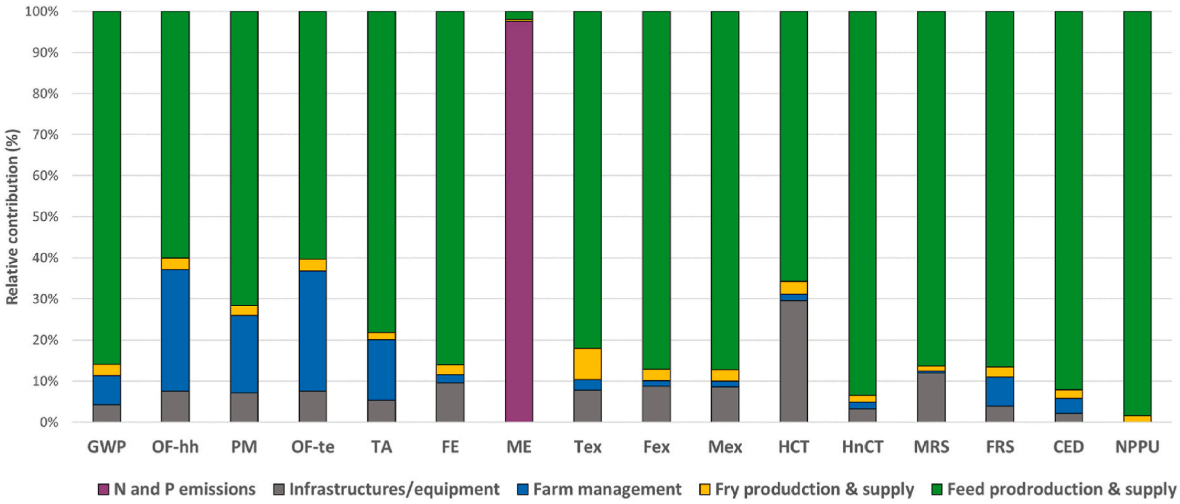

Fig. 2. Relative contribution of impact of sub-processes considered in the analysis, referred to 1 ton of average fish produced. Nitrogen (N) and phosphorus (P) emissions refers to direct emissions due to fish metabolism.

Table 2
Impact categories and related impact for European sea bass (ESB), gilthead sea bream (GSB), and average of both species. Functional unit, 1 ton of fish at the farm gate.

Impact Category	Unit	ESB	GSB	Δ[a]	Average[b]
GWP	kg CO2 eq	3137	2622	−16%	2901
OD	Kg CFC11 eq	0.018	0.014	−18%	0.016
OF-hh	kg NOx eq	12.8	11.3	−12%	12.1
PM	kg PM2.5 eq	6.6	5.6	−14%	6.1
OF-te	kg NOx eq	13	11	−12%	12
TA	kg SO2 eq	24.2	20.6	−15%	22.5
FE	kg P eq	1.4	1.2	−16%	1.3
ME	kg N eq	141	113	−20%	127
Tex	kg 1,4-DCB	8956	7489	−16%	8383
Fex	kg 1,4-DCB	68.4	57.0	−17%	63.2
Mex	kg 1,4-DCB	95.1	79.3	−17%	87.9
HCT	kg 1,4-DCB	89.9	77.6	−14%	84.6
HnCT	kg 1,4-DCB	3516	2905	−17%	3225
MRS	kg Cu eq	17	14.2	−16%	15.7
FRS	kg oil eq	894	749	−16%	827
TCED	MJ eq	87705	72626	−17%	80662
NPPU	kg C	6710	5493	−18%	6135

GWP, global warming potential; OD: Stratospheric ozone depletion; OF-hh Ozone formation, Human health; PM, Fine particulate matter formation; OF-te, Ozone formation, Terrestrial ecosystems; TA, Terrestrial acidification; FE, Freshwater eutrophication; ME, Marine eutrophication; TEx, Terrestrial ecotoxicity; FEx, Freshwater ecotoxicity; Mex, Marine ecotoxicity; HCT, Human carcinogenic toxicity; HnCT, Human non-carcinogenic toxicity; MRS, Mineral resource scarcity; FRS, Fossil resource scarcity; TCED, Total cumulative energy demand; NPPU, Net primary production use.

[a] Relative difference between GSB and ESB impact, calculated as: Delta = (GSB – ESB) ÷ ESB × 100.

[b] Weighted on the annual quantity produced of the two species.

4. Discussion

This study analysed the environmental impact of a large Italian aquaculture company specialized in the production of sea bass and sea bream, detailing its main hotspots. The results of this study can be compared with other study in the literature, although, for the moment, there is only one study concerning Italian aquaculture (Mendoza Beltran et al., 2018). Comparing different LCA studies can be problematic, due to the different contexts or methodological choices made. However, the results illustrated in this study, confirm the largest impact of aquaculture feed for the production of finfish, already reported in most LCA studies (Bohnes et al., 2019). Feed management is the main contributor to most of the impacts analysed. FCR is strictly related to it, as well as emissions of nitrogen compounds into the environment that are the major contributors to marine eutrophication. However, focusing on GWP, this study reports slightly lower results than previous LCA studies focused on GSB and ESB production, although FCR is in line with previous studies. For example, Abdou et al. (2017) reports a GWP of 3182 kg CO_2 eq for ton of ESB and 3669 for GSB with an FCR of 1.88 and 1.85. Nevertheless, they calculated FCR by dividing the total feed intake by net production of species, while, in this study, an economic FCR was considered. Besson et al. (2017) reported a GWP ranging from 2960 to 3636 kg CO_2 eq/ton of fish (for ESB) with an FCR ranging from 1.64 to 2.02, whereas Aubin et al. (2009) reported an impact of 3601 kg CO_2 eq/ton of fish with an economic FCR of 1.77. Finally, the GWP impact reported in this study is significantly lower than the one reported by Jerbi et al. (2012) (17,449 and 11,087 kg CO_2 eq/tonne of live fish weight produced), which refers to an inland RAS system, reflecting the fact that inland systems, mainly due to the huge energy demand, have a higher impact than offshore systems.

In this study, the lower impact (2901 kg CO_2 eq/ton of live fish weight) can be explained by a particular attention paid by the analysed company to feed formulation. Indeed, it is important to note that the weighted average of the inclusion of fishmeal and fish oil in the different feeds fed according to the fish size, is less than 10% and that soybean derived products are not present in the analysed feeds. The latter aspect also avoids the important impact on climate change given by the deforestation associated with it, as it is typically imported from South America. Protein supply is known to be the main environmental hotspot of fish feeding and mitigations must address this first. The use of alternative proteins such as poultry by-product meal and insect meal have good environmental performance and could at least partially replace fishmeal (Maiolo et al., 2020).

In any case, as can be seen from the analysis of the contributions, feed remains the main hotspot in most of the categories analysed, which is consistent with the literature on the topic (Bohnes et al., 2019). Therefore, in order to improve the environmental performance of aquaculture systems, further efforts and research should be conducted to improve all processes that influence feed production and feeding. The inclusion of environmental parameters in optimization programs for aquafeed formulation would be one way to push this improvement, as discussed in Wilfart et al. (2023). Moreover, the reduced inclusion of animal-derived protein explains the reduced impact in the NPPU impact category. In fact the reduction of animal-derived ingredients exponentially reduces the NPPU of this case study (Pauly et Christensen, 1995).

One of the strengths of an LCA study is the simultaneous assessment of different environmental effects or different impact categories. In fact, this study shows that infrastructure and farm management operations during fish farming also have a not insignificant impact, although this impact relates to categories not always reported in previous literature studies. In this regard, as reported in section 3.1, the consumption of large amounts of diesel fuel for rearing management operations such as maintenance, fish moving, feeding, monitoring predominantly effects OF-hh, OF-te, PM, HCT and MRS. Therefore, it would also be of interest to evaluate management optimizations and assess alternative infrastructure materials that can positively affect rearing management. In this regard, Ayer et al. (2016) analysed the impact of Atlantic salmon production with copper alloy net-cage, reporting environmental benefits in all categories analysed. Using alternative cage materials and nets could also bring environmental benefits in ESB and GSB production. Nylon nets have a short life span and net fouling is a serious concern because it reduces water exchanges across the net, reduces dissolved oxygen levels and waste dispersal rate and it can be a reservoir for parasites and possible pathogens, increasing the incidence of potential disease and reducing fish performance (Fitridge et al., 2012). In contrast, copper alloy nets prevent fouling and maintain a healthier environment within the cage and these improvements in culture conditions could in-turn promote improved fish health and growth rates (ICA, 2012). In addition, copper nets have a longer lifespan, are fully recyclable, and require less maintenance. It is well known that the technological level of Mediterranean and Italian aquaculture is not comparable with Atlantic aquaculture (especially when compared to Norwegian Salmon production); on the other hand, this means that there is still room for improvement and that the application of new technologies should be evaluated, as well as the potential environmental benefits it could bring.

As a limitation of this study, it should be underlined that, mainly due to the lack of inventory data, some environmental impacts typically related to aquaculture were excluded from this study. Among these, the potential impact of antibiotics release must be mentioned. This was due to the lack of data on their consumption. Nyberg et al. (2021) underlined the importance of including antibiotics in LCA studies, also proposing some characterization factors for a midpoint category called antibiotic resistance (ABR) enrichment. To the authors' knowledge, the only example of the application of this method in an aquaculture LCA study is found in Sanchez-Matos et al. (2023). Likewise, serious consequences on the marine environment, such as marine debris, ghost fishing and seabed disturbance, are often linked to fisheries, and consequently to aquaculture due to the common inclusion of fishmeal and fish oil in commercial aquafeeds (Ruiz-Salmon et al., 2021). Efforts are being made in recent years to include these impacts, as well as the consequences of plastic litter release and its fate, within LCA frameworks (Henriksson et al., 2012; Woods et al., 2021). All these environmental dimensions, and their relationship with off-shore aquaculture in Italy, are not read by current widespread life cycle methodologies and should definitely be explored in future studies.

5. Alternative scenario (AS)

In the baseline scenario (BS) an UF ratio of 13.4% was calculated based on the information available in literature for GSB and ESB (Ballester-Moltó et al., 2017b). An alternative scenario (AS) has been evaluated in which the amount of uningested feed (UF) has been reduced by 50%, that is in line with the value reported by Ballester-Moltó et al. (2017b). In the AS, a reduction of 50% in the quantity of UF was assumed, while the remaining part was considered as not administered, therefore saved. The quantity of UF was then subtracted from the quantity of feed administered in the BS, keeping the same fish production of the BS. This made it possible to reduce the FCR of GSB and ESB by 6.7% accordingly. The emission of N and P were calculated again for the AS with the updated FCR and UF ratio as showed in Table 3.

Table 3
Main inputs and outputs considered in the analysis for 1 ton of gilthead sea bream (GSB) and European sea bass (ESB) in the alternative scenario (AS).

Inputs			Outputs		
	GSB	ESB		GSB	ESB
Juveniles [#]	2667	3111	Fish [kg]	1000	1000
Feed[a] [kg]	1815.1	2218.5	Nitrogen [kg]	98.6	122.8
N [kg]	131.0	160.1	N dissolved [kg]	85.2	105.4
P [kg]	19.1	23.4	N solid [kg]	13.4	17.4
Electricity[b] [kWh/y]	12.8		Phosphorous [kg]	11.9	15.8
Fuel[b] [L/y]	55.6		P dissolved [kg]	5.4	3.4
Mortality rate [%]	8	20	P solid [kg]	6.5	12.4

[a] N and P concentration of 7.2 and 1.1%, respectively (weighed mean of different feed).

[b] Primary data referred to the fish production and rearing stage.

Fig. 3 shows the comparison results between BS (real case study) and AS for all the impact categories considered. The results showed an overall reduction for all the impact categories considered. For both species, an average reduction about 6% of the impact is gained. As regard GWP, for ESB the impact was reduced from 3137 kg CO_2 eq to 2950, while for GSB from 2622 to 2470 kg CO_2 eq in the AS compared to BS. One of the most affected impact categories is the ME, with a reduction of 15 kg N eq/ton of ESB (from 141 kg N eq to 126, reduction of 10%) and 12 kg N eq in GSB (from 113 to 101 kg N eq, reduction of 11%). The same trend was also observed taking into account the average value of the farm.

The uningested feed is a very important concern, not only from an environmental point of view, but also from an economic one. This alternative scenario was constructed in order to evaluate the sensitivity of the results on the variation of administered feed, that was the main hotspot in the analysis. One strategy to reduce the uningested feed could be increasing the number of daily administrations, which however would require more boat trips resulting in more fuel consumption. Alternatively, a more technological solution could be the installation of an automated feeding and control system in order to better monitor the amount of feed given and encourage a more uniform supply of fish (Føre et al., 2018). Therefore, the application of these technologies should be investigated and evaluated in depth, in order to find the right trade-off between production performances and the inputs needed and to achieve the best system efficiency.

6. Conclusions

This study provided an assessment of the environmental performance associated with the production of ESB and GSB in an Italian offshore farm. As reported by previous studies, feed accounts for the largest share of impact in all impact categories analysed. In this regard, the search for alternative feeds with lower environmental impact is definitely a prerogative of aquaculture. However, the application on a commercial scale of alternative feeds should be evaluated on the entire life cycle of fish production. In addition, this study showed that in certain impact categories, infrastructure and farm management with the high fuel consumption also have an impact of up to 30%. This means that efforts should also be made to improve the technology of the plant itself (alternative materials, feed distribution, management optimization), and even in this direction, there is ample room for improvement.

Finally, as increasingly demanded by policy makers and consumers, an assessment of the economic and social sustainability of the systems should be conducted, in order to have an overall view of the sustainability of this sector.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

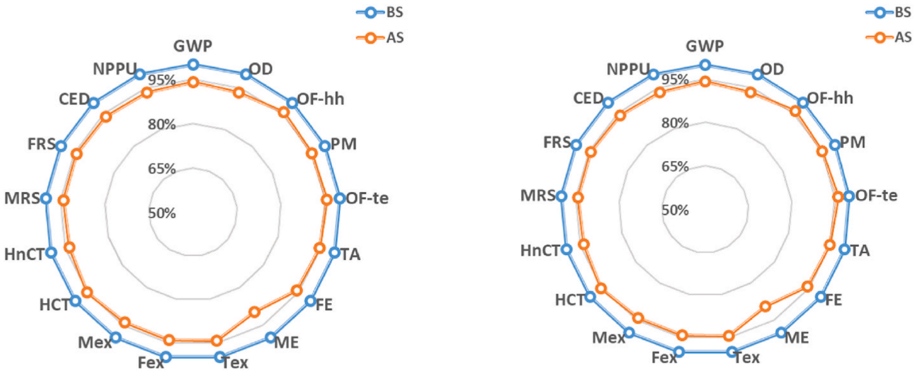

Fig. 3. – Comparison of baseline scenario (BS) and alternative scenario (AS) for European sea bass (left) and gilthead sea bream (right). The definition of the acronyms related to the impact categories is provided in the text.

the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2023.100118.

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