Quantification of the environmental impact of lumpfish farming through a life cycle assessment

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Abstract

Infestations by the salmon louse (*Lepeophtheirus salmonis* Krøyer) represents the major fish health problem that the Atlantic salmon (*Salmo salar*) industry has to face. Sea lice infestation has a large impact on the economy of fish farmers, which are looking for a cost-effective and environmentally sustainable alternative to chemical or mechanical treatments to delouse fish. The biological control of sea lice using the so-called cleaner fish has been individuated as a feasible delousing approach of Atlantic salmons. In particular, in recent years the lumpfish (*Cyclopterus lumpus*) has been extensively farmed to be used as a 'biological weapon' in salmon farming because of its effectiveness in delousing also in harsh environmental conditions. However, the environmental impact of lumpfish farming is still largely unknown. Thus, the present study aimed at assessing the potential environmental impact of lumpfish production through a life cycle assessment (LCA) approach. Feed and electricity consumption, both for 8 of the 18 evaluated midpoint indicators, are the main responsible of the environmental load while for the Freshwater and Marine eutrophication about 90% of the impact is related to the emission of nitrogen and phosphorous compounds by fishes. These data lay the foundation for further, sustainable improvement of lumpfish farming.

Keywords: lumpfish, aquaculture, life cycle assessment

1. Introduction

Farming of Atlantic salmon (*Salmo salar*) represents one of the most flourishing component of the finfish aquaculture sector worldwide, supplying high-end markets and serving the demand for capture fisheries products. Farmed Atlantic salmon has become a super commodity, as pointed out by its year-round, worldwide availability, product consistency and high production volume (Eagle et al., 2004; Naylor et al., 2005). However, the infestation caused by the salmon louse (*Lepeophtheirus salmonis* Krøyer), a copepod ectoparasite that grazes on the skin and mucosal tissue of fish, causing infections, osmotic stress and death (Johansen et al., 2011), represents the main issue that the Atlantic salmon industry has to face (Imsland et al., 2014). Sea lice infestation has a notable impact on the economy of Atlantic salmon farmers because of the costs behind the treatment procedures to delouse fish, as well as the reduction of fish growth, the increase of feed waste and the decrease of market quality of the final product (Powell et al., 2018). For instance, the estimated cost of sea lice for Norwegian fish farmers only exceeds 150 m€/year (Bergheim, 2012).

The Atlantic salmon industry is struggling sea lice infestation relying on different medicinal treatments, including the application of chemotherapeutic or bath treatments with hydrogen peroxide and organophosphates or synthetic pyrethroids, as well as feeding fish with food medicated with emamectin benzoate (Denholm et al., 2002). Although medicinal treatments are effective in delousing the salmon ectoparasite, the continuous and frequent use of pyrethroids and emamectin benzoate induced the development of resistance in sea lice (Igboeli et al., 2012), leading to a reduced effectiveness of the treatment and 50% increased proportion of ineffective treatments from 2002 to 2006 (Lees et al., 2008). Alternatively, non-medicinal approaches such as sea lice skirts or traps, snorkels, thermal treatments, flushers, lasers, bubble curtains were used, but many of them are still in the development or investigational phases and results in delousing need to be confirmed.

To overcome these limitations, a cost-effective and environmentally sustainable alternative to medicinal and non-medicinal treatments has been recently individuated and refers to the biological control using the so-called 'cleaner fish'. The use of cleaner fish is particularly attractive because it can reduce the use of chemical medications, be more cost-effective than other approaches and potentially less stressful to farmed salmons (Liu and Vanhauwaer Bjelland 2014; Treasurer, 2013). Labrid fish, mainly the ballan wrasse (*Labrus bergylta*) and the goldsinny wrasse (*Ctenolabrus rupestris*) have been used to delouse Atlantic salmon in net pens for 30 years (Bjordal, 1991), because they significantly reduce the prevalence of sea lice in farmed salmons (Treasurer, 2013). However, the use of labrid fish has a substantial limitation because they experience winter dormancy and do not feed at water temperature below 6 °C (Kelly et al., 2014), precluding their use as cleaner fish over the winter (Treasurer, 2013). Thus, an alternative cleaner fish with active feeding behaviour at low water temperatures has been identified in the lumpfish (*Cyclopterus lumpus*; Imsland et al., 2014a,b,c; 2015a). In fact, the lumpfish continue feeding also at temperatures as low as 4 °C (Nytrø et al., 2014), allowing delousing of salmon over the year. Moreover, the lumpfish can easily rear under captivity and reach the appropriate size to be deployed in salmon farms in as little as 4 months, while the ballan wrasse typically requires 1.5 years (Helland et al., 2014). For these reasons, the number of cleaner fish used by the salmon farming industry has increased exponentially since 2008, and almost 26 million were used in 2015 in salmon farming in Norway alone. It has been estimated that 50 million cleaner fish will be required by Atlantic salmon industry within 2020, the most of which will be lumpfish. To satisfy this huge demand, commercial production of lumpfish has grown exponentially in the last few years, so that 11.8 million juveniles were reared in Norway during 2015 (Norwegian Directorate of Fisheries, 2015) and over than 20 million in 2016 (Nodland, 2016). Although the use of lumpfish is considered a sustainable approach to reduce the environmental impact of Atlantic salmon farming, to date information on the environmental impact of lumpfish farming is lacking.

Thus, the present study was aimed and investigating the environmental impact of one of the main lumpfish farming facilities in Norway by using a life cycle assessment (LCA) approach. LCA is an ISO-standardized biophysical accounting framework commonly used to compile an inventory of material and energy inputs and outputs typical of all the stages of a product life cycle and to quantify its contributions to a specified suite of resource use and emissions-related environmental impact categories (Guinee et al., 2001).

2. Materials and Methods

2.1 Lumpfish farming

A schematic representation of the lumpfish farming process is reported by Powell et al. (2018). In the present study we relied on data from one of the main land based lumpfish farming in Norway, operating in flow-through seawater system. The facility who has collaborated and supplied with data for this study prefer to remain anonym for commercial reasons. The selected lumpfish production plant produces more than 1 million lumpfish yearly, while the total market need is about 40-50 million cleaner fish. Moreover, this plant has been one of the first to farm lumpfish as cleaner fish against sea lice and have therefore established aquaculture practice that have been replicated in others facility in the whole Norway. The water flow taken from deep water pass through sand filter, UV filter and oxygenation before flowing into the fish tanks in order to optimize the water quality and promote fish wellness and health. Moreover, the division of the farm were juvenile is produced utilize a heat exchanger for increase the temperature of the water and increase the growth rate. Briefly, lumpfish in the facility are farmed as follows. Wild-caught lumpfish are used as a broodstock to produce juveniles to be used as cleaner fish in Atlantic salmon sea pen. Sexually-mature adults are typically wild-caught during the spawning season using gill nets deployed in shallow waters (up to ~30 m deep) close to the shore. In captivity, fertilization is performed through the ‘dry method’, that is mixing the sperm with eggs and adding seawater to activate the sperm. Sperm is collected following dissection of the testes, which are then macerated and passed through a sieve. Female abdomen is squeezed to obtain eggs, which are transferred in small tanks to be fertilized by male sperm. Fertilized eggs are quickly transferred in upwelling incubators consisting of 14 L hoppers loaded with an average 0.4 - 0.9 kg of eggs, corresponding to about 20,000 to 45,000 of eggs per hopper. Seawater flow rate is maintained at 15 L/min during incubation, and then increased to 20 L/min when they became eyed-eggs and the oxygen uptake need increase. Overall, hatching period lasts about 250 – 300 degree days in the temperature range between 7 to 12 °C. Considering that the temperature in the hatching division of the plant we considered is maintained at ~ 10 °C daily, the hatching of lumpfish eggs requires ~ 30 days. After hatching, larvae are transferred to bigger tanks of 1 m^3 dimension and feed with dry food with granule size from 75 to 250 µm. Then, in the following 6 to 9 months the development of the juvenile happens almost exponentially from less than 0.1 gram to an average of 30-35 grams. The fishes are split several times during the development phase and divided in 1 to 3 m^3 tanks accordingly to the fish size and density need. During this growth phase the lumpfish are still feed with dry food granulate with size range from 250 µm to 840 - 1,410 µm. The preferable water temperature is maintained around 12 °C in order to optimize the growth rate. Almost four week before releasing them in the sea cages with Atlantic salmon, the lumpfish get vaccinated and feed with granule feed with size between 0.5 and 2.0 mm. When the post vaccination incubation time is over, the cleaner fish are deployed into net pen in the sea together with Atlantic salmon or rainbow trout (*Oncorhynchus mykiss*). An amount of lumpfish ranging between 2 and 15% of the total number of Atlantic salmon individuals reared in each sea net pen are included. Considering limitations for fish density of 25 kg/m^3 and maximum allowable biomass of 200,000 fish per unit (Liu et al., 2016), the amount of lumpfish added to the net pens can range from 4,000 and 30,000 individuals.

The manager of the farm is thereafter responsible to the acclimation of the lumpfish to its new environment. This happen mainly through the installation of artificial plastic seaweed in the net pen, whose main function is to allow the lumpfish individuals to hide themselves and attach to the substrate with their ventral sucker, as their semi pelagic feature require. One other important action made from the sea farm manager to acclimate the lumpfish is to feed them with granulate food in the range 2.0 to 3.0 mm on a daily basis.

2.1 Goal and scope definition

The goal of this LCA study is to evaluate the environmental impact of the lumpfish farming facility. As a cleaning fish, lumpfish is used for sea lice control. Although different sea lice pest control practices (i.e., biological, chemical and mechanical control) are applied, mainly in Atlantic salmon aquaculture, there is a lack of information on the environmental impacts on pest control measures used in salmonids aquaculture.

This study contributes to fill the gap of knowledge about the impact of lumpfish production and provides an important information for decision makers to make more sustainable choices in lumpfish farming and also in the application of treatments for sea lice control in Atlantic salmon farming.

The functional unit was defined as 1 kg of live weight of lumpfish. Even if the number of fish could be uses as functional unit the mass was preferred because lumpfish can be used at different size and weight. Besides this, this choice is in agreement with previously carried out LCA study about cleaning fish (Philis et al., 2021).

The system boundaries used, were from cradle to farm gate, including all processes and materials that were used prior to the grow-out phase of the lumpfish within the land based farm, as well as the processes and materials in the grow-out phase itself. The prior processes include the production of juveniles, feed and medicinal treatments, as well as energy use and input transport.

2.3 Life cycle inventory

For the assessment of the environmental impacts of the different elements involved in the production of lumpfish, primary and secondary data were used that were obtained from a wide range of sources.

Primary data regarding the consumption of the different production factors (e.g., diesel, electricity, chemicals, feed, liquid oxygen and so forth) were directly collected at the lumpfish farm by means of questionnaires and by interview with the farm operators. Table 1 reports the main production factors consumed during lumpfish production.

Table 1 – Main inventory data for lumpfish production expressed for the selected FU.

Production Factors	Amount	Unit
Electricity	26.923	kWh
Diesel	31.923	g
Oxygen, liquid	43.846	g
Antibiotics	0.152	g
Feed	0.771	kg

Secondary data about the emissions related to the combustion of fuel as well as to the output of nitrogen (N) end phosphorous (P) compounds as metabolic waste by fish were estimated. Fuel combustion were assessed according to Spielmann et al. (2007).

The output of N and P metabolic wastes by fish depends by a variety of endogenous and exogenous factors, such as genetics, life stage, size, rearing system and diet (Mock et al., 2019). Ammonia is predominant type of N excreted, and high levels of ammonia excretion may be due to high protein intake or inadequately formulated diets which provide unbalanced protein synthesis. Phosphorus excretion usually accounts for 69-86% of dietary P and is associated with the sources, which are used in different ways by different species (Lazzari and Baldisserotto, 2008). In this study, the emission of N and P compounds were estimated according to Cho and Kaushik (1991).

Background data about the unitary impact of fuels, chemicals and feed were retrieved by Ecoinvent v 3.6. The inventory data were processed using the software SimaPro 9.1.1.

2.4 Life cycle impact assessment

The inventory data were converted into potential environmental impacts using the characterization factors defined by Recipe LCIA method (Goedkoop et al., 2009; Huijbregts et al., 2017). In detail, the following midpoint impact categories were considered:

- Global warming (GW, expressed as kg CO_2 equivalent or eq.),
- Stratospheric ozone depletion, (ODP, expressed as mg CFC11 eq.),
- Ionizing radiation (IR , expressed as kBq Co-60 eq.),
- Ozone formation, Human health, (HOPF, expressed as g NOx eq.),
- Fine particulate matter formation, (PMFP, expressed as g $PM_{2.5}$ eq.),
- Ozone formation, Terrestrial ecosystems, (EOFP, expressed as g NOx eq.),
- Terrestrial acidification, (TAP, expressed as g SO_2 eq.),
- Freshwater eutrophication, (FEP, expressed as g P eq.),
- Marine eutrophication, (MEP, expressed as g N eq.),
- Terrestrial ecotoxicity, (TETP, expressed as kg 1,4- dichlorobenzene - DCB),
- Freshwater ecotoxicity, (FETP, expressed as kg 1,4-DCB),
- Marine ecotoxicity, (METP, expressed as kg 1,4-DCB),
- Human carcinogenic toxicity, (HTPc, expressed as kg 1,4-DCB),
- Human non-carcinogenic toxicity, (HTPnoc, expressed as kg 1,4-DCB),
- Land use (LU, expressed as m^2a crop eq.),

- Mineral resource scarcity, (SOP, expressed as g Cu eq.),
- Fossil resource scarcity, (FFP, expressed as kg oil eq.),
- Water consumption (WD, expressed as m^3).

3. Results

Table 2 reports the potential environmental impact for the selected functional unit (1 kg of live-weight lumpfish) while the contribution analysis is shown in Figure 2.

Table 2 – Absolute potential environmental impact for the selected functional unit.

Impact category	Acronym	Unit	Score
Global warming	GW	kg CO_2 eq.	2.384
Stratospheric ozone depletion	ODP	mg CFC11 eq.	9.615
Ionizing radiation	IR	kBq Co-60 eq.	0.375
Ozone formation, Human health	HOPF	g NOx eq.	6.501
Fine particulate matter formation	PMFP	g $PM_{2.5}$ eq.	3.005
Ozone formation, Terrestrial ecosystems	EOFP	g NOx eq.	6.615
Terrestrial acidification	TAP	g SO_2 eq.	9.890
Freshwater eutrophication	FEP	g P eq.	9.535
Marine eutrophication	MEP	g N eq.	14.066
Terrestrial ecotoxicity	TETP	kg 1,4-DCB	6.252
Freshwater ecotoxicity	FETP	kg 1,4-DCB	0.196
Marine ecotoxicity	METP	kg 1,4-DCB	0.236
Human carcinogenic toxicity	HTPc	kg 1,4-DCB	0.081
Human non-carcinogenic toxicity	HTPnoc	kg 1,4-DCB	2.685
Land use	LU	m^2a crop eq.	7.258
Mineral resource scarcity	SOP	g Cu eq.	8.359
Fossil resource scarcity	FFP	kg oil eq.	0.394
Water consumption	WD	m^3	0.834

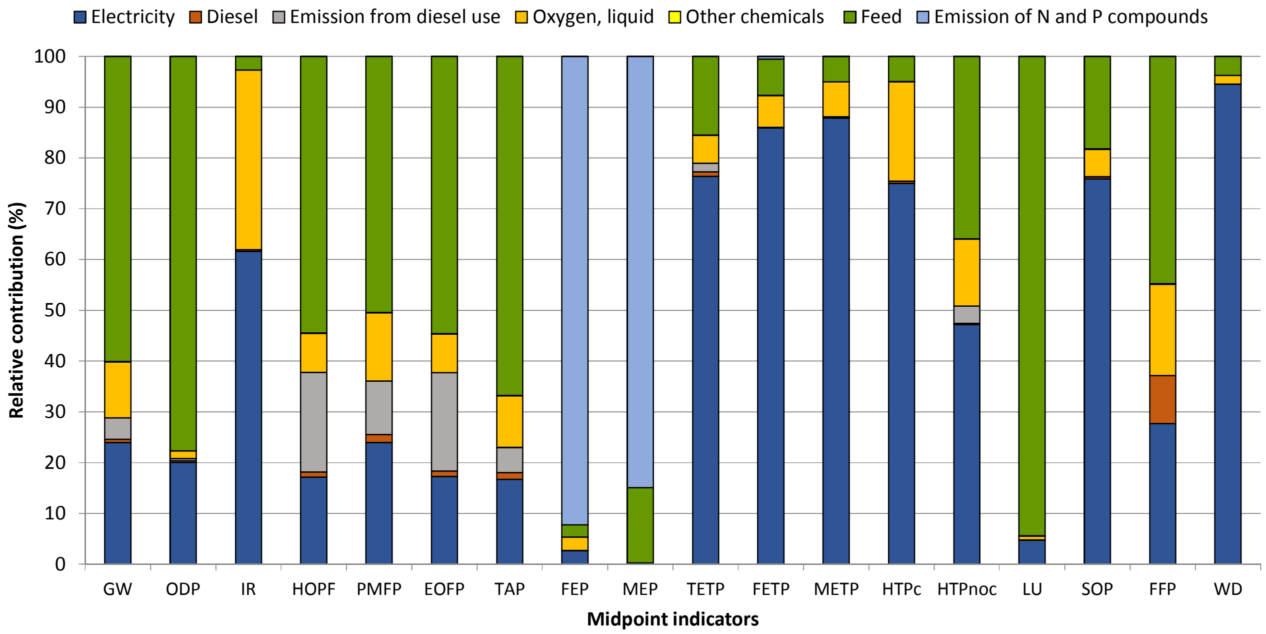

Figure 2 – Contribution analysis for lumpfish production in terms of midpoint indicators.

For 8 of the 18 evaluated potential environmental impacts (i.e., GW, ODP, HOPF, PMFP, EOFP, TAP, LU and FFP), feed consumption is the main responsible of the environmental load with a share of the total impact ranging from 44% for Fossil resource scarcity to 94% for Land Use. The impact of feed consumption is mainly related to the production of soybean meal, rapeseed and wheat grain.

For other 8 impact categories (IR, TETP, FETP, METP, HTPc, HTPnoc, SOP and WD) the main driver of the environmental results is the electricity consumption while, for the remaining two (FEP and MEP), more than 90% of the environmental load is related to the emission of N and P compounds by fishes. For Freshwater eutrophication (FEP), the emission of phosphorous compounds is the main responsible of the environmental impact, while Marine eutrophication (MEP) is mainly related to ammonia emissions.

Except for the liquid oxygen consumption in IR (accounting for 35% of the impact) and for the emissions related to diesel fuel combustion for the Ozone formation, Human health (HOPF) and Ozone formation, Terrestrial ecosystems (EOFP) (19% of the impact), the other production factors consumed and the other emission sources play a minor role.

An uncertainty analysis was carried out with the Monte Carlo technique (1,000 iterations and a confidence interval of 95%) to test the robustness of the achieved results. The analysis (detailed results reported in the Supplementary Material in Table S2 and Figure S1) shows a low uncertainty for all the evaluated impact categories except than for IR and WU where the coefficient of variation is 120% and 474%, respectively.

4. Discussion

The results of the present LCA study detail the environmental impact of a lumpfish aquaculture facility. As to date the lumpish is the most abundant fish species farmed to be used as a cleaner fish, and not for human consumption, the impacts originated by the production of this species cannot be directly compared with that of fish that are commonly farmed to serve as food. However, our findings can be compared with those from a recent study that estimated six impact categories for farmed lumpfish, as well as farmed and fished wrasses, used as cleaner fish in delousing farmed Atlantic salmon (Philis et al., 2021). Even if the comparison among LCA studies can be affected by different system boundary and assumptions the two studies selected the same Functional unit and the same LCIA method. Between the two studies, some differences emerged. In fact, the present study showed that GW and MEP impacts of the facility we focused on were lower, but the LU impact was higher, compared to those reported by Philis and co-authors (2021). In contrast, a similar impact in terms of METP was noted. These discrepancies are due to uncertainties and differences during the LCA modelling, from data collection to selection and use of data. In addition, the impact of farmed lumpfish estimated by Philis and co-authors (2021) derived from data collected in different lumpfish facilities, which exploiting different farming technologies and processes returned variable inventory data. For instance, one of the main differences in lumpfish production processes in terms of energy consumption concerns the heating of the water inside the farm in order to increase the metabolism and consequently the hunger of the fish. Interestingly, the same work showed that the impact related to the farming of wrasse was generally higher compared to the lumpfish mainly in terms of GW, WD and METP (Philis et al., 2021). These differences can be due to the longer production cycle of wrasse compared to the lumpfish (3-fold longer) and an unusually high electricity demand despite the use of heat-exchangers, partly due to the longer production cycle, higher sea-water temperature requirements compared to the lumpfish (Philis et al., 2021), and the use of flow-through rearing technology (Brooker et al., 2018). Moreover, farmed wrasse also requires live feeding through the hatching phase and is particularly prone to disease and adaptation difficulties (Helland et al., 2014). However, despite our effort to compare the impacts of different cleaner fish value chains, a significant gap of knowledge remains to couple life cycle emissions generated by the farming, distribution, and use of the cleaner fish and their potential different delousing efficiencies in the salmon net pens (Philis et al., 2021). Intra- and inter-specific differences in delousing efficiencies depend on species types, behaviour, survival and adaptation rates, response to stress, growth speed, operating sea-water temperature and swimming abilities (Brooker et al., 2018). Although some studies demonstrated that lumpfish (Eliasen et al., 2018; Imsland et al., 2018) and wrasse (Leclercq et al., 2014; Skiftesvik et al., 2013) are effective delousers, there is high level of uncertainty regarding their efficiency. For this reason, in the present study we performed a comparison of the environmental impacts caused by two farmed cleaner fish assuming the same delousing efficacy, but in further studies this issue should need to be carefully considered.

Lastly, we attempted to estimate the impact of using lumpfish to produce a ton of Atlantic salmon. First, the salmon production (in tons of live salmons ready for slaughterhouse) within a net pen was estimated by considering the volume of a single net pen and the maximum allowed stock density of salmons that can be reared in the net pen (25 kg/m^3; Liu et al., 2016) where conventional farming is applied. Considering that the size of net pens varies among Atlantic salmon rearing facilities, we suggested two different scenarios: the first one assuming the use of middle-size net pen (90 m in diameter, 30 m in depth; volume = 19,347 m^3) and the second one assuming a large-size net pen (160 m in diameter, 40 m in depth; volume = 81,528 m^3). Then, as the maximum amount of salmons that can be included in a net pen accounts for 200,000 specimens, we estimated the minimum (2%) and the maximum (15%) amount of lumpfish that can be added to a single net pen of both sizes, corresponding to 4,000 and 30,000 individuals, respectively. We calculated the impact, in terms of Global warming, Terrestrial acidification and Freshwater eutrophication per ton of salmon reared in middle-size and large-size net pen, as well as per ton of lumpfish (both minimum and maximum amount). Lastly, we calculated the contribution of the use of lumpfish to the environmental impact due to produce a ton of salmon. We considered the impact to produce a ton of Atlantic salmon in terms of global warming (2793.5 kg CO_2 eq./ton), terrestrial acidification (25.1 g SO_2 eq./ton) and freshwater eutrophication (66.5 g P eq./ton) as the mean of each specific endpoint according to previous LCA studies of the impact of Atlantic salmon aquaculture (see Philis et al., 2019 and references therein). In middle-size net pen, the addition of the minimum or maximum amount of lumpfish accounted for the 1.76% and 13.23% in terms of global warming, while in large-size net pens, the contribution accounted for 0.42% and 3.14%, respectively. Similarly, the share of the Atlantic salmon impact related to the use of lumpfish in terms of Terrestrial acidification and freshwater eutrophication was lower in the scenario that considered large-size net pen (0.19 – 1.44% for g SO_2 eq.; 0.07 – 0.53% for g P eq.) than middle-size net pen (0.81 – 6.10% for g SO_2 eq.; 0.29 – 2.22% for g P eq.). These results seem to confirm that open net farming with large net pen volumes, exceeding 60,000 m^3 in one pen, are more energy- (and cost-) efficient than smaller ones (Ziegler et al., 2013). However, these estimates must be considered with caution because they relied on assumptions and might suffer a moderate degree of uncertainty.

4.1 Strategies to improve sustainability of lumpfish aquaculture

Our data highlighted the manifold environmental impacts of lumpfish farming that cannot be neglected and need to be explored in depth to opportunely enlarge its environmental sustainability. To increase the sustainability of lumpfish aquaculture, some technical improvements of the facility, as well as of the farming processes, could allow to reduce the contribution of some impact category. Concerning the farming processes, a series of steps forwards, including improvements in collection and transport of wild breeders, reproduction procedures and development of broodstock reared entirely in captivity, might be undertaken to make lumpfish farming for sea-lice control more sustainable (Powell et al., 2018). To date, nearly all the lumpfish used as cleaner fish in Atlantic salmon farming industry come from wild-caught parents, which after being used as breeders are sacrificed, affecting natural populations of the species. This issue is particularly relevant because the lumpfish is considered a moderate to high vulnerable species (Froese and Pauly, 2014) and it has been classified as near threatened (NT) in the IUCN Red List (Lorance et al., 2015). Thus, to limit the use of wild breeders and to keep pace with the growing demand of lumpfish for sea lice control, the breeding cycle needs to be closed in captivity (Anon, 2015) and future production needs to be derived entirely from selected farmed strains (Powell et al., 2018).

Another strategy to reduce the collection of wild breeders concerns the cryopreservation of milt from wild male (Powell et al., 2018). Sperm cryopreservation is a well-known advantageous methodology for fish reproduction in aquaculture, mainly in seasonal breeders (Cabrita et al., 2005; Martínez-Páramo et al., 2017), that allows the reduction of wild breeders maintaining a high fish production. Few studies validated methods for cryopreserving milt of lumpfish, suggesting that this strategy can be used for hatchery management in lumpfish aquaculture (Pountney et al., 2020) and to maintain a stable production throughout the year of lumpfish juveniles (Norðberg et al., 2015). These improvements should return two crucial outcomes. On one hand, decreasing the wild-catch of breeders should reduce the environmental impacts related to fishing activities of breeders (e.g., fuel consumption, release of hazardous contaminants, use of chemicals during transport to the farming facility), while on the other hand, closing the breeding cycle in captivity should allow to select strains with the desired compromise of property as high delousing performance, fish health and resistance, growth rate and so on. In fact, lumpfish families show a dissimilar efficiency in feeding on sea-lice (Imsland et al. 2016), suggesting the existence of a genetic component for sea-lice consumption that might be used to select specific strains with high affinity to prey sea-lice (Powell et al., 2018).

Selecting strains with slow growth could be also advantageous because lumpfish show less interest regarding eating sea-lice at a size of about 300–400 g (Anon 2014). Thus, strain selection should reduce the amount of lumpfish to be produced, farmed and transferred to Atlantic salmon net pens for delousing activities, decreasing the environmental impact of lumpfish farming. Another crucial issue that could increase the sustainability of lumpfish farming concerns the re-use of individuals after their deployment in Atlantic salmon net pens (Powell et al., 2018). To date, lumpfish are used only for a salmon production cycle. Whilst the most of them died within net pens, the survivors are generally culled because of impairment of their health status due sub-optimal rearing conditions and the subsequent decrease in delousing efficiency. As this practice has been criticized because wasteful and with diverse animal welfare implications (Anon 2013; Farm Animal Welfare Committee 2014), lumpfish survived to the harsh conditions experienced during a salmon production cycle could be used to create a broodstock of high-resistant individuals to be used in captive breeding programmes. Considering the high mortality of lumpfish in the net pen, also due to predatory behaviour and bites by salmons (Espmark et al., 2019), further input of fish result as necessary to guarantee the delousing activity. Developing high-resistant strains from post-deployment individuals, should allow to prevent new introductions of cleaner fish and, consequently, to reduce the number of individuals to be farmed and the impact of farming activities.

The optimization of larval production might reduce the impact of lumpfish aquaculture. The selection of well-adapted strains in captivity and the improvement of formulation of diets in early developmental periods should contribute to reduce the high mortality occurring during larval weaning, specifically during the transition from live to dry feeds (Powell et al., 2018). Improving the composition of the diet and/or optimizing the amount of feed administered to larvae during post-hatching periods should be particularly important considering that feed consumption has been identified as the main responsible of environmental impacts in terms of midpoint indicators of lumpfish farming.

5. Conclusions

The present study detailed the environmental impacts of lumpfish farming to be used as cleaner fish in Atlantic salmon aquaculture. Considering the importance of the use of cleaner fish, and in particular of the lumpfish, in delousing salmonids in open-water net pens, our data lay the foundations to optimize the entire process of lumpfish farming, promoting a transition towards a more sustainable production. For instance, considering the impacts pointed out by this study, some mitigation measures could be implemented. As the main contributor to the environmental impacts of lumpfish aquaculture come from feed, decreasing the feed administration or improving the feed formulation could be a strategy to be implemented. At the same time, reducing the energy consumption in the lumpfish facility (e.g., to heat the water) and the use of fuel (e.g., reducing the distances of transport or the number of fishing operations to collect breeders) might reduce the environmental impacts of lumpfish farming.

In addition, our findings are crucial to compare the environmental impacts of biological, mechanical, and chemical treatments exploited by salmon farmers to delouse fish, as well as to estimate the contribution of each single treatments to the salmon footprints.

Moreover, the results of this study can be used by owner and decision maker at the cleaner fish land based facilities as a tool for a confrontation of lumpfish production impact with the emerging farming activity of wrasse species used as supplementary cleaner fish as ballan wrasse (*Labris bergylta*). Policy maker could also benefit from the outcome of this study because the LCA is a standardized assessment tool for potential improvement of the juridical frame necessary to regulate the new emerging delousing methods and best practice. Last but not least, this information should drive salmon farmers towards the application of one or treatment mix returning the lowest environmental impacts without undermining fish welfare, fish production and economic gain.

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Conflict of Interest

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:

Author contribution

Federico Haaland Gaeta: Data collection, Investigation, Writing - review & editing; **Marco Parolini**: Writing - original draft, Supervision; **Jacopo Bacenetti**: Formal analyses, Writing - review & editing