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Comparative environmental impact assessment of aquafeed production: Sustainability implications of forage fish meal and oil free diets

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ABSTRACT

The environmental sustainability of aquaculture food production systems is of critical concern due to its rapid expansion as the fastest growing major food production sector in the world. Among the parameters that contribute to the overall environmental impacts of aquaculture marine-based protein production, aquafeed is identified as an impact hotspot. There is consequently a need to seek more environmentally sustainable aquafeeds to mitigate the adverse environmental impacts associated with aquaculture food production.

The environmental and economic sustainability of aquafeeds can be improved using two main approaches: (a) optimizing finite resources use (e.g. fish meal and fish oil), and (b) mitigating waste generation and emissions. A variety of ingredients have been previously proposed, investigated, and utilized to accomplish these strategies, while maintaining acceptable food production efficiencies. However, comprehensive evaluation of the environmental sustainability of aquafeeds with respect to variable ingredients, both in terms of resource use and waste emission has not been conducted.

In this work, a holistic life cycle impact assessment of twelve practically formulated and utilized aquafeeds has been performed to provide a comparative evaluation of different aquafeed's environmental impacts, considering resource use (biotic resource use, water intake, and fossil fuel depletion) and emission-based impact categories (ozone depletion, global warming, photochemical smog, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory effects, and ecotoxicity). Results indicate that the investigated fish meal free diets do not, on the whole, result in a significant decrease in environmental impacts with respect to the use of biotic resources. However, if the substituted ingredients would not propose elevated impacts (e.g. blood meal), these diets can potentially lower the overall environmental impacts of aquafeed production mainly with respect to relevant emission-based indicators (e.g. global warming, eutrophication, ecotoxicity). Findings demonstrate that the investigated fish oil free diets can potentially lower the use of biotic resources. However, to prevent burden shifting, strategies to provide nutrient-rich oils with minimal energy requirement need to be undertaken.

1. Introduction

Due to the increasing global population (DESA, 2017) and concurrent rise in of consumption marine-based proteins per capita (FAO, 2009), aquaculture is the fastest growing major food production sector in the world. According to the Food and Agriculture Organization of the United Nations (FAO), the average annual growth in aquaculture production between 2000-2016 was 5.8%. This growth is expected to continue, and it is predicted that 60% of the fish available for human consumption will be provided by aquaculture in 2030 (Department A.O.o.t.U.N.F., 2018). In order to support sustainable aquaculture development and support the current growth of aquaculture, there is a critical need to mitigate the environmental impacts of aquaculture food production systems; FAO, 2018 Papatryphon et al., 2004).

Aquafeed has been previously identified as one of the most environmentally impactful parameters of aquaculture systems in conventional impact categories (e.g. global warming) (Bosma et al., 2011; Samuel-Fitwi et al., 2013; Ghamkhar et al., 2019; Wu et al., 2019). In addition, it is estimated that the aquaculture sector consumes 68.2% of total global fish meal production and 88.5% of total global fish oil production, making it highly dependent on marine capture fisheries (e.g. forage fish) for sourcing key dietary nutrient inputs (e.g. amino acids) (Tacon and Metian, 2008). The high dependency of ever-growing aquaculture food production on fish meal and fish oil, as well as the upward trends in fish meal and fish oil prices (Tacon and Metian, 2008;

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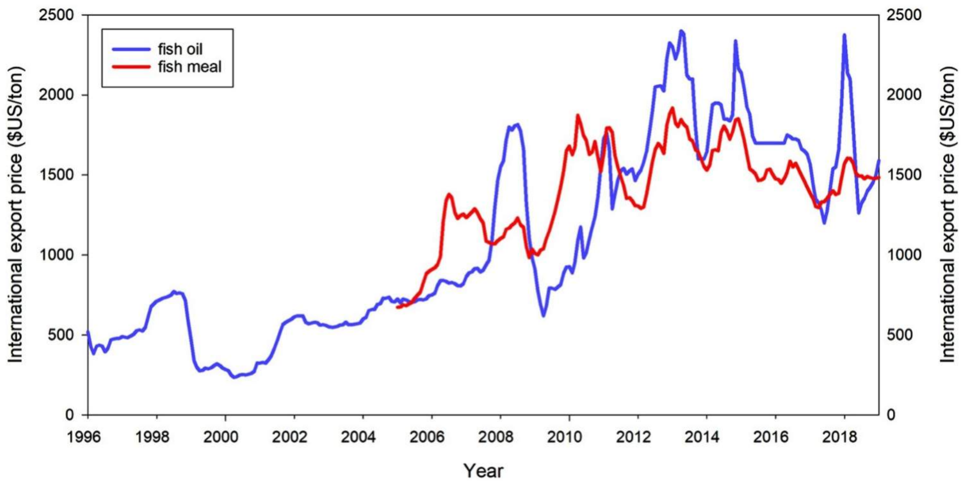


Fig. 1. International export price trends for fish meal (from January 2005 to June 2019) and fish oil (from January 1996 to June 2019) in US$ per metric ton.

Msangi et al., 2013) have challenged the long-term ecological and economical sustainability of aquaculture food production systems. The international export fish meal and fish oil prices based on US Dollar / ton over time are illustrated in Fig. 1 (FAO, 2019).

Aquaculture demand of finite marine resources is predicted to outstrip global supplies within the next decade (Pelletier and Tyedmers, 2007). Therefore, to achieve sustainable aquaculture production, producers are seeking alternative feed ingredients to substitute marine-based fish meal and fish oil in the feeding formulations (Bendiksen et al., 2011).

Various alternative ingredients, derived from plants and animals, have been formulated and used in an effort to fully or partially substitute fish meal and fish oil in aquafeeds (Forster et al., 2003; Davidson et al., 2016; Stone et al., 2005; Lazzarotto et al., 2018; Oliva-Teles et al., 2015). As a result, trends indicate reduced inclusion rates of fish meal and fish oil in industrial aquafeeds (Naylor et al., 2009). However, total fish meal and fish oil use have continued their upward consumption trends due to the overall increase in global aquaculture production (Tacon and Metian, 2008; Naylor et al., 2009). It is anticipated that fisheries and aquaculture industries will expand their efforts to substitute marine-based ingredients with practical alternative nutrients in future years.

Despite the vital need to move towards aquafeeds with less dependency on biotic resources to provide essential nutrients, it is necessary to quantitatively evaluate the environmental impacts of aquafeeds containing different ingredients. Previous evaluations have typically used a limited set of impact categories (global warming, eutrophication, acidification, and energy demand (Bohnes and Laurent, 2019)), and neglected some crucial indicators of aquafeeds and aquacultures environmental sustainability, such as biotic resource depletion (Bohnes and Laurent, 2019; Henriksson et al., 2012). To prevent unintended consequences through burden shifting, an evaluation should be performed utilizing a comprehensive set of relevant impact categories, both in terms of resource depletion (e.g. water intake, biotic resource use) (Goddard and Al-Abri, 2019; Calone et al., 2019; Damerau et al., 2019) and pollutant emissions (e.g. eutrophication, photochemical smog) (Ghamkhar, 2018; Ghafari et al., 2019; Silvenius et al., 2017; Zheng et al., 2019). Moreover, it is also critical to consider the efficacy of these aquafeeds with respect to the quantity and quality of the produced fish.

Life cycle assessment (LCA) has been applied previously to aquafeeds (Papatryphon et al., 2004; Ghamkhar et al., 2019; Silvenius et al., 2017; Pelletier et al., 2009; Aubin et al., 2009; Hognes et al., 2012). Quantification of the environmental impacts of different aquafeeds provides the opportunity to perform a comprehensive impact analysis and comparison among alternative3 production scenarios (Ianchenko and Proksch, 2019). Previous studies have performed LCA on hypothetical aquafeeds, revealing that feed ingredient composition improvement of aquafeeds is necessary to mitigate the use of fishery resources (e.g fish meal) and nutrient emissions at the farm (Papatryphon et al., 2004; Pelletier and Tyedmers, 2007). However, they have neglected to analyze the impact of the different theoretical aquafeeds on the quality of the seafood produced.

In this work, LCA is performed on twelve successfully formulated and tested (actually fed to aquaculture species) aquafeeds, containing various ingredients (e.g. fish meal free and fish oil free diets). Environmental impacts with respect to biotic resource use, water intake, and conventional Tool for the Reduction and Assessment of Chemicals and other environmental Impacts (TRACI) impact categories (Bare et al., 2012) are quantified and evaluated to provide a holistic analysis on the environmental impacts of traditional aquafeeds as well as alternatives that are utilizing different strategies for fish meal and fish oil replacement. In the end, suggestions to shift toward less environmentally impactful aquafeeds, considering the protein inclusion of investigated diets and fish production (feed efficiency), are made.

2. Methodology and evaluation criteria

Life Cycle Assessment (LCA) is used as the comprehensive framework to evaluate the environmental impacts associated with products or processes throughout their entire life cycle. According to the International Standards Organization (ISO14040), LCA consists of four main steps (phases) (ISO, 1997). In the goal and scope definition step, the motivation to perform LCA, functional unit, product system boundary, and data parameters are defined. In the inventory stage, resources consumed and emissions to the environment at all stages of the process lifetime, from the raw material extraction to the disposal of waste, are quantified (ISO, 1997; Guinée, 2002). In the third step, recognition and evaluation of key issues are made. In the end, conclusions and recommendations are made in interpretation step (Lee and Inaba, 2004). In this study, the SimaPro 8.2.0 modeling platform was used for LCA, using databases from Agri-footprint (Durlinger et al., 2014), Ecoinvent-3 (EcoInvent, 2014), and United States Life Cycle Inventory (USLCI) (Norris, 2004) databases. For processes with multiple products (e.g. for fish meal from trimmings), mass allocations have been selected to handle multi-functionality.

2.1. Statistical analysis

For all investigated impact categories except BRU, the uncertainties associated with the unit processes in the life cycle database were analyzed using Monte-Carlo simulations in SimaPro 8.2.0, for 1000 runs to

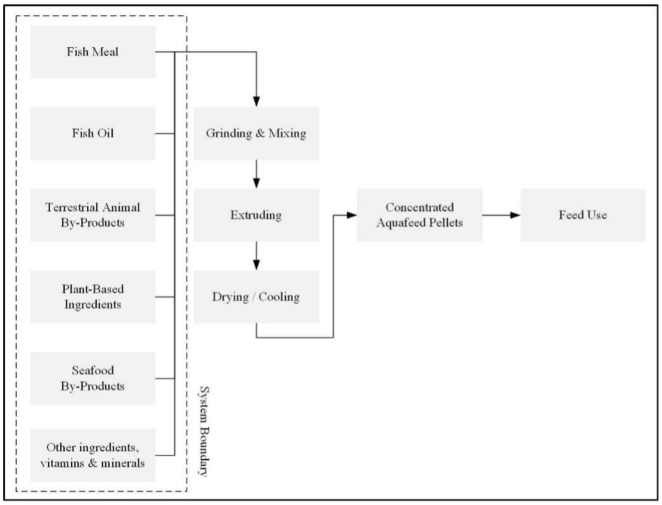


Fig. 2. Life Cycle Inventory framework for aquafeeds production.

the 95th confidence interval. Uncertainty analysis for BRU impact category is not conducted due to the lack of data on the unit processes distribution.

To determine if there is a statistically significant difference between the mean impacts for two selected independent datasets from Monte-Carlo simulation, t-test analysis (two-sample mean-comparison test) with a confidence level of 95 is performed using Stata/SE 16.0. For any performed *t*-test, *t*-value (t) and *p*-value (p) were calculated. If $p < 0.05$, it is considered as a statistically significant.

2.2. Goal and scope: system's boundary

The main goal of this study is to determine the comparative environmental impacts of aquafeed production, based on varied practiced ingredients. In order to investigate the varying environmental impacts among aquafeeds with different ingredients, a cradle to gate (ingredients material acquisition and manufacturing) LCA approach is selected to be executed on successfully formulated, tested and used aquafeeds. The included/excluded parameters in the assessment criteria is illustrated in Fig. 2.

The environmental impacts of aquafeed production, using different ingredients will be evaluated and assessed based on associated ingredients and impact characterization factors. The impacts associated with the proceeding processes (i.e. grinding, extruding, drying, etc.) are excluded from the assessments due to similar requirements and processes among different diets.

2.3. Functional unit

The functional unit (FU) is a quantified description of a studied system and it provides a reference by which inputs and outputs can be related and compared (Rebitzer et al., 2004). In many comparative analytical techniques, including LCA, functional unit is a central consideration (Pourzahedi and Eckelman, 2015). Mass-based functional units have been used previously for investigating the impacts of varying aquafeeds (Pelletier and Tyedmers, 2007, Iribarren et al., 2012, Yacout et al., 2016). However, the comparative evaluation of aquafeeds' impact based on unit mass of produced aquafeed as the only FU ignores the variation in aquafeeds' nutritional characteristics, properties, and ultimate efficiency. To account for properties and characteristics of aquafeeds, two alternate functional units are utilized in this study: (a) aquafeeds unit protein provision (De Silva and Anderson, 1994), and (b) seafood unit live weight production (Papatryphon et al., 2004; Aubin et al., 2009; Abdou et al., 2018). Consideration of varying FUs has also provided the opportunity to increase transparency of the results across studies with different perspectives regarding aquafeeds production with respect to the system's final product (Ghamkhar et al., 2019). As different aquafeeds propose varying nutritional characteristics and are ultimately tested on varying species, the normalization of results based on protein inclusion (as the major consideration for fish meal and fish oil replacement strategies (De Silva and Anderson, 1994; Hua et al., 2019)) is expected to provide the most precise comparative results. Therefore, unit provision of protein is considered as the concentrated FU for comparisons in this study.

2.4. Quantification methods

To provide a comprehensive impact assessment, all impact categories that are characterized by US EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2.1 are investigated. The investigated conventional TRACI 2.1 impact categories (as well as their abbreviation and unit) are: Ozone Depletion (OD, kg CFC-11 eq), Global Warming (GW, kg CO_2 eq), Photochemical Smog (PS, kg O_3 eq), Acidification (AC, kg SO_2 eq), Eutrophication (EU, kg N eq), Human Health Carcinogenics (HHC, CTUh), Human Health Non-Carcinogenics (HHNC, CTUh), Respiratory Effects (RE, kg $PM_{2.5}$ eq), Ecotoxicity (EC, CTUe), and Fossil Fuel Depletion (FF, MJ surplus).

For each midpoint environmental impact category, the total amount of chemical emission (or resource utilized) is multiplied by its estimated potency. This methodology (TRACI 2.1) is reported to be based on the best available data and models in the US, allowing a desired level of comprehensiveness and accountability (Bare et al., 2012).

In addition to the conventional TRACI 2.1 impact categories, Water Intake (WI, Liters) and Biotic Resource Use (BRU, kg C eq) are recognized as two important impact categories in food production processes, that are rarely investigated in aquaculture-related studies and LCA (Bohnes and Laurent, 2019; Lippiatt, 2007). For Water Intake, the Bees 4.0 tool is used in order to address the direct and indirect water resource use of processes (resource pollution is excluded in this impact category) (Lippiatt, 2007). For Biotic Resource Use, calculations are performed based on the methodology described by Pauly and Christensen (1995) (Pauly and Christensen, 1995). For agricultural ingredients, the carbon content represented in the crop fraction of the plant is quantified (Pelletier and Tyedmers, 2007). For ingredients derived from plants (e.g. concentrates and extractions), production yields were also assigned to obtain the proper impacts based on unit mass of dry matters. Biotic resource use for animal-based ingredients (fishery-derived or terrestrial) was calculated with the following formula:

$$P = \frac{m/x}{9} \cdot 10^{(T-1)} \tag{2}$$

In which, P is the mass (g) of carbon appropriated, m is the mass (g) of animal-based ingredient, x is the animal-based ingredient production yield (mass of ingredient/mass of wet weight animal), and T is the trophic level of the organism. For the processes with multiple products, mass allocation is selected to assign appropriate impacts to each product.

Results based on these assessment methods are expressed in terms of their potential environmental impacts rather than actual damage levels, which is following the problem-oriented midpoint approach (Pelletier and Tyedmers, 2010).

2.5. Feed conversion ratio (FCR)

An accurate assessment of feed intake is one of the most challenging aspects of the aquaculture industry to quantify (Glencross et al., 2007), due in part to differences in nutritional requirements, such as fatty acids and carbohydrates, among different fish species (Oliva-Teles et al., 2015). However, the effect of diet on an aquatic species' growth and performance is an important principle that needs to be investigated. The efficiency of nutrient intake by animals is usually characterized as feed conversion ratio (FCR), which is calculated by Eq. (1):

$$Feed\ Conversion\ Ratio = \frac{1}{Feed\ Conversion\ Efficiency} = \frac{Consumed\ dry\ weight\ food}{Gained\ live\ weight\ product} \quad (1)$$

Typical FCRs for animal production (using commercial feeds and intensive production methods) are as follows: 6-10 for beef cattle, 2.7-5 for pork, 1.7-2 for poultry, and 1.0-2.4 for farmed fish and shrimp (Fry et al., 2018). Seafood production yields lower FCRs compared with other farmed terrestrial animals, indicating higher harvest yields for aquatic species. However, specific FCRs for seafood production depend on many factors such as diet type, species, and the harvesting environment characteristics.

2.6. Life cycle inventory: aqua diets

There are a large number of alternative feed ingredients that can be substituted for fish meal and fish oil, potentially leading to more sustainable formulations (Gatlin et al., 2007; Bell and Waagbø, 2008; Pelletier et al., 2018). Naylor et al., have classified these alternatives into the following groups: plant-based proteins/lipids, single cell protein/oils, rendered terrestrial animal products, and seafood by-products (Naylor et al., 2009). Following the aforementioned grouping approach, twelve different aquafeeds that have been successfully formulated and tested to produce seafood were extracted from the literature (to ensure practicality of diets usage). FMOC-1, FMOC-2, and FMOC-3 refer to the diets that are fish meal and fish oil containing with varying ingredients and protein content (42.3%, 41.0%, and 30.1% respectively) (Davidson et al., 2016; Carter et al., 2003; Akiyama, 1990). FMF-1-T and FMF-2-T refer to the fish meal free diets, in which fish meal is replaced with terrestrial poultry by-product and terrestrial blood meal, respectively. Resulting protein contents are 38.5% for FMF-1-T, and 30.8% for FMF-2-T (Rossi and Davis, 2012; El-Sayed, 1998). FMF-3-P and FMF-4-P refer to the fish meal free diets, in which fish meal is replaced with plant-based peanut meal and soybean meal, respectively. Resulting protein contents are 39.9% for FMF-3-P, and 38.5% for FMF-4-P (Adelizi et al., 1998). FMF-5-S refers to the forage fish meal free diet, in which fish meal is replaced with fish processing industry by-products. Resulting protein content is 34.0% (Forster et al., 2004). FOF-1 and FOF-2 refer to the fish oil free diets, in which fish oil is replaced with vegetable (canola) oil, and both vegetable-based (canola) and single-cell protist-based (Thraustochytrid) oils (Carter et al., 2003; Byreddy, 2015). Resulting protein contents are 39.8 for FOF-1 and 39.1 for FOF-2 (Carter et al., 2003). Finally, FMOF refers to the fish meal and fish oil free diet, in which full replacement of fish meal and oil with terrestrial meal (poultry by-product), plant-based meal (mixed nuts), and seafood by-product (whitefish trimming) ingredients in undertaken. Resulting protein content is 42.2% (Davidson et al., 2016). Summarized specifications regarding the aquafeeds nutritional characteristics, targeted animal (type and life stage), and the reported consecutive effects of feeding the aquafeed to animal (e.g. growth performance, water quality, etc.) are tabulated in Table 1. Additional specifications regarding the ingredients materials, amounts, corresponding LCI database, assumptions, and comments are provided in Tables S1-S12 of the supplementary material (supplementary information, SI).

The tabulated summary of varying diet aids to (a) acquire the environmental impacts levelized by protein provision (as a major nutrient necessary for aquatic species), (b) acquire the environmental impacts levelized by live-weight seafood production (as the proceeding output of aquafeed production), and (c) acknowledge the primary feeding characteristics used in the investigated studies.

2.7. Cost estimation for GW and BRU

Social cost of carbon (SC-CO_2) is an estimation of long-term economic harm (in dollars), which is caused by the impacts due to the emission of 1-ton carbon dioxide (CO_2) into the atmosphere. Despite the lack of precise information regarding the consequences of CO_2 emission, SC-CO_2 accounts for changes in net agricultural productivity, property damages from increased flood risk, human health, and changes in energy system costs (e.g. reduced costs for heating and increased costs for air conditioning). An estimation of $42/ton of CO_2, in 2007 US$ (which equals $52/ton of CO_2, in 2019 $US) is reported as SC-$CO_2$ for 2020, based on percent discount rate (Interagency Working Group on Social Cost of Carbon, 2013). This value is used for comparisons and trade-off analysis in the discussion section.

Biotic resource use (BRU, as an estimation of net primary production use) is the amount of net flux carbon (biomass produced from photosynthesis) sequestered from the atmosphere to the system, in the sense of not being available for other purposes (Pelletier and Tyedmers, 2007; Aubin et al., 2009). Richmond et al. estimated empirical prices for net primary production (based on the contribution of ecosystem services to GDPs) and assigned them to different nations (Richmond et al., 2007). A price of $47/$10^6$ kg C, as 1996 US$ (which equals $77/$10^6$ kg C, as 2019 $US) is selected as the average of the range reported for the US estimated shadow price for net primary production (Richmond et al., 2007). This value is used for comparisons and trade-off analysis in the discussion section.

3. Results

3.1. Aquafeeds comparative environmental impacts

A quantitative assessment of 12 different aquafeeds formulations, attributed to each diet's inputs and outputs is performed with 12 environmental impact categories. Relative results based on three FUs are illustrated in Fig. 3. Absolute results are provided in Table S13 of the SI. For WI and all TRACI impact categories, *t*-test analysis based on 1 kg protein is also performed among FMOC diets vs alternative replacement diets (based on protein inclusion) to evaluate the significance of difference among investigated substitution alternatives. Summarized t-test analysis results are provided in Table 2. Expanded results regarding the Monte-Carlo simulation and *t*-test analysis are provided in Tables S14 to S25 and S29 of the SI.

As shown in Fig. 3, considering any FU, none of the formulated feeds outperforms other aquafeeds for all investigated environmental impacts.

As shown in Fig. 3 and Table 2, FMF-1-T presents comparable BRU relative to the FMOC diets (higher than FMOC-3, and lower than FMOC-1, FMOC-2, and FMOC-4). However, an overall improvement with respect to the other investigated indicators is assessed by shifting from FMOCs to FMF-1-T (reduction of impacts compared to all FMOC diets in 6/11 impact categories). FMF-2-T presents lower BRU relative to the FMOC diets. However, an overall increase of impacts with respect to the other investigated indicators is assessed by shifting from FMOCs to FMF-2-T (increase of impacts compared to all FMOC diets in 8/11 impact categories). FMF-3-P presents comparable BRU relative to the FMOC diets (higher than FMOC-3, and lower than FMOC-1, FMOC-2 and FMOC-4). Regarding the other investigated indicators, FMF-3-P presents comparable impacts relative to the FMOC diets. FMF-4-P presents comparable BRU relative to the FMOC diets (higher than FMOC-3, and lower than FMOC-1, FMOC-2 and FMOC-4). However, an overall improvement with respect to the other investigated indicators is assessed by shifting from FMOCs to FMF-4-P (reduction of impacts compared to all FMOC diets in 10/11 impact categories). FMF-5-S presents comparable BRU relative to the FMOC diets (higher than FMOC-3, and lower than FMOC-1, FMOC-2, and FMOC-4). However, and overall improvement with respect to the other investigated

Table 1
Summary of compiled formulated and tested aquafeeds.

Aquafeed	Study	Targeted species	Life stage	Pr%	FCR	Additional specifications
FMOC-1	Davidson et al., 2016 (Davidson et al., 2016)	Atlantic salmon (*Salmo salar*)	Post-smolt	42.3	0.90	FMOF diet resulted in higher TP, cBOD, and TSS** in the effluent compared to FMOC-1.
FMOC-2	Carter et al., 2003 (Carter et al., 2003)	Atlantic salmon (*Salmo salar)*	Pre-smolt	41.0	0.86	No significant difference in fish weight gain and feed consumption among FMOC-2, FOF-1, and FOF-2.
FMOC-3	Akiyama, 1990 (Akiyama, 1990)	Carp	N/S*	30.1	2.10	Soybean meal is used to partially replace fish meal.
FMOC-4	Aas et al., 2019 (Aas et al., 2019)	Atlantic salmon (*Salmo salar)*	N/S*	35.6	1.21	This diet describes the average utilization of feed resources in salmon production in Norway during 2016. It includes all losses of feed and fish.
FMF-1-T	Rossi Jr. & Davis., 2012 (Rossi and Davis, 2012)	Pompano *(Trachinotus carolinusL.)*	Juvenile	38.5	2.50	Fish meal is substituted with poultry by-product. Reductions in weight gain, feed efficiency, and protein and energy retention were observed compared to fish meal containing diets.
FMF-2-T	El-Sayed., 1998 (El-Sayed, 1998)	Nile tilapia *(Oreochromis niloticus L.)*	Fingerlings	30.8	2.60	Fish meal is substituted with blood meal. Reductions in fish performance (growth rate, protein efficiency) were noticed.
FMF-3-P	Adelizi et al., 1998 (Adelizi et al., 1998)	Rainbow Trout *(Oncorhynchus mykiss)*	Juvenile	39.9	1.21	Fish meal is substituted with peanut meal. Peanut meal replacement have resulted in lower weight gain and higher protein efficiency ratio.
FMF-4-P	Adelizi et al., 1998 (Adelizi et al., 1998)	Rainbow Trout *(Oncorhynchus mykiss)*	Juvenile	38.5	1.25	Fish meal is substituted with soybean meal. Soybean meal replacement have resulted in significantly higher weight gain and protein efficiency compared to commercial diet.
FMF-5-S	Forster et al., 2004 (Forster et al., 2004)	Pacific white shrimp *(Litopenaeus vannamei)*	N/S*	34.0	1.33	Fish meal is substituted with Alaska fish processing industry by-products (primarily pollock). There were no significant difference in shrimp performance parameters (growth, FCR, survival) compared to the fish meal containing control diet.
FOF-1	Carter et al., 2003 (Carter et al., 2003)	Atlantic salmon *(Salmo salar)*	Pre-smolt	39.8	0.84	Fish oil is substituted with canola oil. No significant difference in fish weight gain and feed consumption among FMOC-2, FOF-1, and FOF-2.
FOF-2	Carter et al., 2003 (Carter et al., 2003)	Atlantic salmon *(Salmo salar)*	Pre-smolt	39.1	0.91	Fish oil is substituted with thraustochytrid and canola oil. No significant difference in fish weight gain and feed consumption among FMOC-2, FOF-1, and FOF-2.
FMOF	Davidson et al., 2016 (Davidson et al., 2016)	Atlantic salmon *(Salmo salar)*	Post-smolt	42.2	0.89	FMOF diet resulted in higher TP, cBOD, and TSS** in the effluent compared to FMOC-1.

* Not Specified.
** TP: Total Phosphorus, cBOD: carbonaceous Biochemical Oxygen Demand, TSS: Total Suspended Solids.

Fig. 3. Relative environmental impacts of aquafeeds based on (a) unit mass of aquafeed produced, (b) unit mass of protein inclusion, and (c) unit mass of live-weight seafood produced. Impact categories consist of OD, GW, PS, AC, EU, HHC, HHNC, RE, EC, FF, WI, and BRU. Different background colors indicate different formulation strategies (gray: fish meal and oil containing, pink: fish meal free, blue: fish oil free, green: fish meal and oil free). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

indicators is assessed by shifting from FMOCs to FMF-5-S. FOF-1 presents lower BRU relative to the FMOC diets. However, FOF-1 presents comparable impacts with respect to the other investigated indicators relative to FMOCs. FOF-2 presents lower BRU relative to the FMOC diets. However, an overall increase of impacts with respect to the other investigated indicators is assessed by shifting from FMOCs to FOF-2 (increase of impacts compared to all FMOC diets in 5/11 impact categories). FMOF presents comparable BRU relative to the FMOC diets (higher than FMOC-3, and lower than FMOC-1, FMOC-2, and FMOC-4). Additionally, FMOF presents comparable impacts with respect to the other investigated indicators relative to FMOCs.

Considering an overall reduction of BRU and an overall reduction of other environmental impacts as the primary and secondary objective of diets replacement, analyses indicate that FOF-1, in which fish oil is substituted with canola oil, is the best diet alternative (lower in BRU, comparable in other impacts). FMF-1-T, FMF-4-P, and FMF-5-S, in which fish meal is substituted with poultry by-product, soybean meal, and fish trimming by-product respectively, yielded other desirable alternatives to FMOCs (comparable in BRU, mainly lower in other impacts).

3.2. Contribution analysis

To demonstrate which parameters contributed the most to impacts for each category and diet, a contribution analysis is performed. Results are summarized in Table 3.

With respect to BRU, fish oil has the highest contribution of impact in all the diets that contain it as an ingredient (from either forage or trimming resources). For fish oil free diets (FOF-1 and FOF-2), fish meal has the highest contribution of impact.

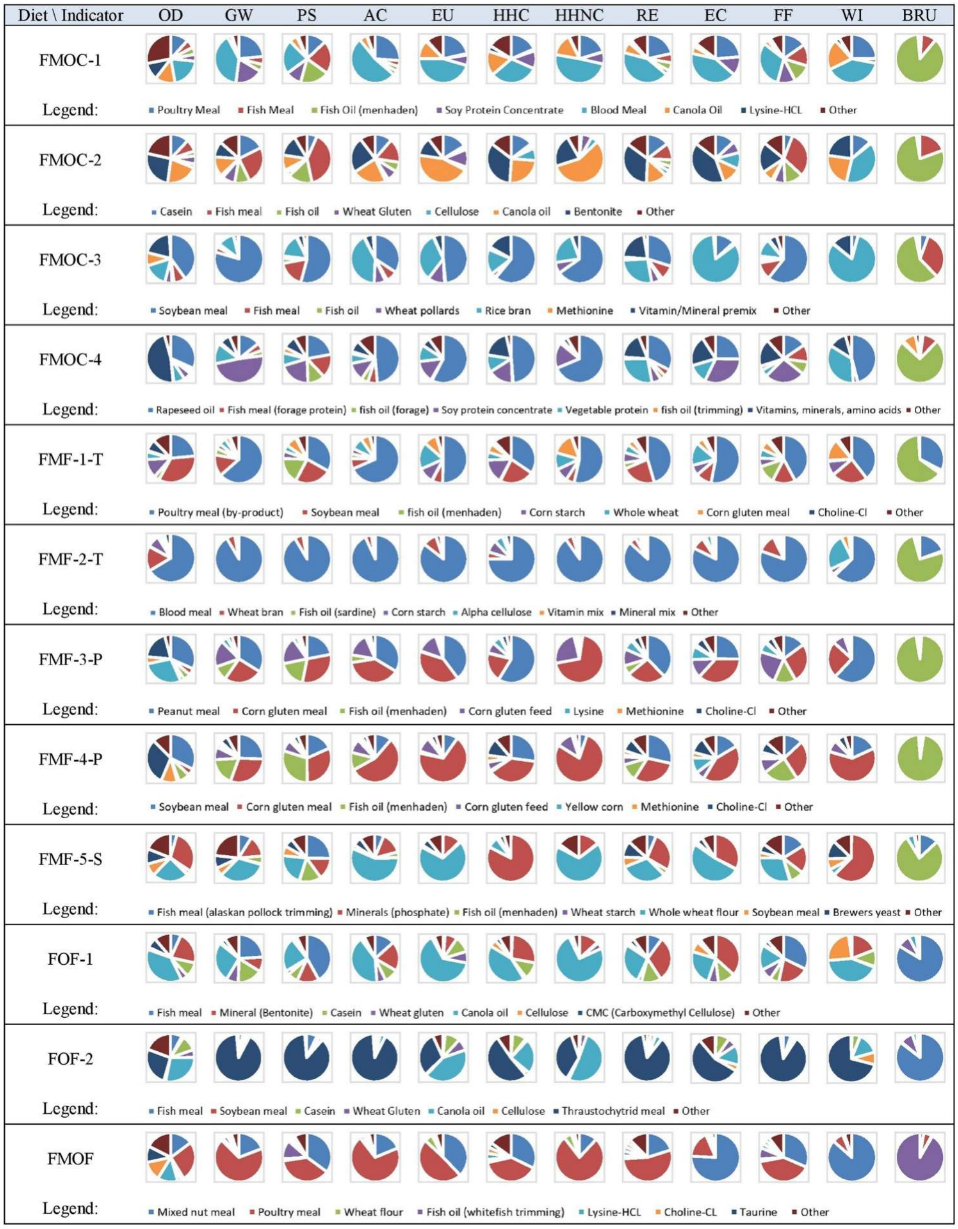
With respect to the other investigated impacts, blood meal has contributed the highest to the impacts of FMOC-1, despite the higher

Table 2
Summarized results for the mean comparison *t*-test analysis (confidence level = 95) among FMOC diets vs. fish meal and fish oil replacement diets (based on 1-kg protein).

	Compare Aquafeed → With Aquafeed ↓	FMOC-1	FMOC-2	FMOC-3	FMOC-4
OD	FMF-1-T	Green	Green	Green	Green
	FMF-2-T	Red	Red	Red	Yellow
	FMF-3-P	Green	Yellow	Red	Green
	FMF-4-P	Green	Green	Green	Green
	FMF-5-S	Green	Green	Green	Green
	FOF-1	Green	Red	Red	Green
	FOF-2	Yellow	Red	Red	Green
	FMOF	Green	Red	Red	Green
GW	FMF-1-T	Green	Red	Green	Green
	FMF-2-T	Red	Red	Red	Red
	FMF-3-P	Green	Red	Green	Green
	FMF-4-P	Green	Green	Green	Green
	FMF-5-S	Green	Green	Green	Green
	FOF-1	Green	Red	Green	Green
	FOF-2	Red	Red	Red	Red
	FMOF	Green	Red	Green	Green
PS	FMF-1-T	Green	Green	Green	Green
	FMF-2-T	Red	Red	Red	Red
	FMF-3-P	Green	Red	Green	Green
	FMF-4-P	Green	Green	Green	Green
	FMF-5-S	Green	Green	Green	Green
	FOF-1	Green	Green	Green	Green
	FOF-2	Red	Red	Red	Red
	FMOF	Green	Red	Green	Green
AC	FMF-1-T	Green	Red	Green	Green
	FMF-2-T	Red	Red	Red	Green
	FMF-3-P	Green	Red	Red	Green
	FMF-4-P	Green	Green	Green	Green
	FMF-5-S	Green	Green	Green	Green
	FOF-1	Green	Red	Green	Green
	FOF-2	Red	Red	Red	Red
	FMOF	Green	Red	Red	Red
EU	FMF-1-T	Green	Red	Green	Green
	FMF-2-T	Red	Red	Red	Red
	FMF-3-P	Green	Red	Green	Green
	FMF-4-P	Green	Green	Green	Green
	FMF-5-S	Green	Red	Green	Green
	FOF-1	Green	Red	Green	Green
	FOF-2	Green	Red	Green	Green
	FMOF	Green	Red	Red	Green
HHC	FMF-1-T	Green	Green	Green	Green
	FMF-2-T	Red	Red	Red	Red
	FMF-3-P	Red	Red	Red	Green
	FMF-4-P	Green	Green	Green	Green
	FMF-5-S	Green	Red	Green	Green
	FOF-1	Green	Red	Green	Green
	FOF-2	Red	Red	Red	Yellow
	FMOF	Green	Red	Green	Green
HHNC	FMF-1-T	Green	Red	Green	Green
	FMF-2-T	Red	Red	Red	Red
	FMF-3-P	Green	Red	Green	Green
	FMF-4-P	Green	Red	Green	Green
	FMF-5-S	Green	Green	Green	Green
	FOF-1	Green	Red	Green	Green
	FOF-2	Green	Red	Red	Green
	FMOF	Green	Red	Green	Green
RE	FMF-1-T	Green	Green	Green	Green
	FMF-2-T	Red	Red	Red	Red
	FMF-3-P	Green	Red	Red	Green
	FMF-4-P	Green	Green	Green	Green
	FMF-5-S	Green	Green	Green	Green
	FOF-1	Green	Red	Red	Green
	FOF-2	Red	Red	Red	Red
	FMOF	Green	Red	Red	Green
EC	FMF-1-T	Green	Red	Green	Green
	FMF-2-T	Red	Green	Green	Red
	FMF-3-P	Green	Red	Green	Green
	FMF-4-P	Green	Green	Green	Green
	FMF-5-S	Green	Red	Green	Green
	FOF-1	Green	Red	Green	Green
	FOF-2	Green	Red	Green	Green
	FMOF	Red	Red	Green	Red
FF	FMF-1-T	Green	Green	Green	Green
	FMF-2-T	Red	Red	Red	Red
	FMF-3-P	Green	Red	Green	Green
	FMF-4-P	Green	Green	Green	Green
	FMF-5-S	Green	Green	Green	Green
	FOF-1	Green	Green	Green	Green
	FOF-2	Red	Red	Red	Red
	FMOF	Green	Red	Green	Green
WI	FMF-1-T	Green	Green	Green	Green
	FMF-2-T	Red	Red	Red	Red
	FMF-3-P	Red	Red	Yellow	Red
	FMF-4-P	Green	Green	Green	Green
	FMF-5-S	Green	Green	Green	Green
	FOF-1	Red	Yellow	Green	Yellow
	FOF-2	Green	Green	Green	Green
	FMOF	Red	Red	Red	Red

* Stata/SE 16.0 T-test (two-sample mean comparison test)
* Confidence level = 95
* Green indicates significant impact reduction (p<0.05).
* Red indicates significant impact increase (p<0.05).
* Yellow indicates non-significant difference (p>0.05).

Table 3
Relative contribution of aquafeeds ingredients to the total associated environmental impacts.



quantity of other ingredients inclusion in this diet (e.g. fish meal and wheat flour). Blood meal also has the dominant contribution of impacts in FMF-2-T diet, in which fish meal is substituted with blood meal by design. Canola oil and bentonite (mineral) have contributed the highest to the FMOC-2 impacts. Soybean meal and rice bran were the top contributors of FMOC-3 impacts. For FMOC-4, rapeseed oil has the highest share to the overall impacts. Poultry meal and soybean meal were the highest contributors of impacts for FMF-1-T. For FMF-3-P, peanut meal and CGM (Corn Gluten Meal) have the highest portion of impacts. For FMF-4-P, soybean meal and CGM has contributed the most to the impacts. Minerals and wheat flour have revealed the highest contribution of impacts for FMF-5-S. Canola oil and minerals have resulted the most of impacts for FOF-1. For FOF-2, Algae-based Thraustochytrid meal has the overall highest contribution of impacts. Finally, poultry meal and mixed nut meal has contributed the highest to the overall impacts of FMOF.

Based on the aforementioned results from contribution analysis for FMOC diets, ingredients other than fish meal and fish oil have assessed to be the highest contributors of the environmental impacts in TRACI and WI impact categories (all except BRU). Therefore, the overall improvement for FMF-1-T, FMF-4-P, and FMF-5-S is due to either (a) relative lower impact of these diets high impact contributors (e.g. poultry meal, CGM, minerals, wheat flour, etc.) compared to the FMOCs high impact contributors or (b) relative lower inclusion of ingredients with high impact contributors, determined in FMOCs (e.g. soybean meal).

The overall increase of impacts for FMF-2-T (in all investigated impact categories except BRU) is attributed to the higher impact of blood meal compared to the FMOCs impact hotspots (e.g. canola oil, bentonite, rice bran, etc.). Further investigation into the blood meal process reveals that the high environmental impacts of blood meal in conventional impact categories are mainly due to the process' material-based inputs (chicken, pig, and beef co-products), which contribute to > 82.8% of overall impacts in all TRACI impact categories (Table S26). CGM is another identified impact hotspot ingredient, recognized in both

FMF-3-P and FMF-4-P. The high environmental impacts of CGM production in most of the conventional impact categories (all TRACI except PS) are mainly due to corn harvest and storage process (>77.18%, Table S27).

Finally, the overall increase of impacts in GW, PS, AC, RE, and FF for FOF-2 is due to (a) relatively high energy consumption for the production of single-cell protest-based thraustochytrid meal (Table S3) and (b) high contribution of electricity consumption (>85.5%) in the environmental impacts of thraustochytrid meal production in the aforementioned 5/12 impact categories (Table S28). Therefore, in order to prevent an increase of environmental impacts in impact categories rather than BRU (burden shifting), there is a demand to either (a) replace fish oil by a nutrient-equivalent oil (canola oil in the case studied) with relatively low energy consumption or (b) decrease the energy demand of algae-based oil production with comparable quantity of required nutrients (e.g. industrial optimization of thraustochytrid meal production).

4. Discussion

4.1. Burden shifting

Despite the crucial importance of impact mitigation with respect to biotic resource depletion in the aquafeed industry, it is important to evaluate broader environmental impacts of aquafeed production using a comprehensive set of impact categories. This provides the opportunity mitigate unintended consequences of food production based on a systems thinking approach (Tlusty et al., 2019). The alternative fish meal free and fish oil free diets should not only perform better with respect to BRU (less impacts), but also should not pose additional environmental risks due to the elevated impacts in other impact categories. As shown in Fig. 4, the reductions in the aquafeeds' BRU shadow price (from $15.3, attributed to FMOC-1 to $0.68, attributed to FOF-2) have not resulted in similar trend with respect to the social cost of carbon. In fact, SC-CO_2 is the highest for FOF-2 ($1452.7), while this diet proposes the least BRU shadow price.

In spite of the use of different monetary valuation methodologies and estimation criterion for SC-CO_2 and BRU, the comparison of trends and the order of magnitude for the estimated prices highlights the importance of exercising further caution in substituting ingredients to achieve alternatives with lower overall environmental impacts.

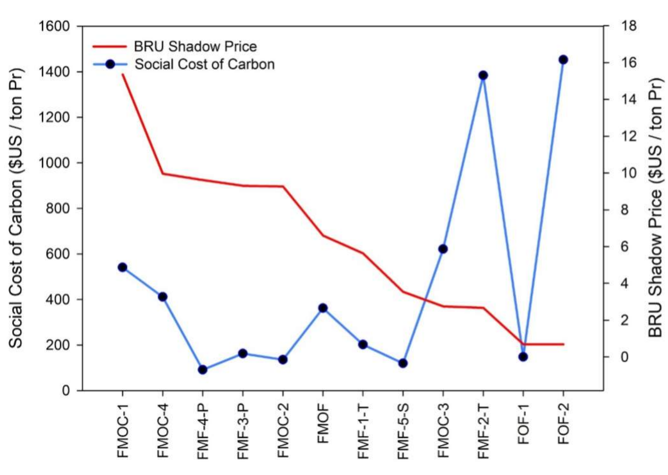


Fig. 4. Relative social cost of carbon (left vertical axis) and BRU shadow price (right vertical axis) for different aquafeeds, levelized based on protein (Pr) inclusion. Prices are based on 2019 $US.

4.2. In-practice challenges

In addition to environmental considerations for different aquafeeds, it is essential to investigate practical challenges that feed production industries might face when utilizing alternative ingredients. For example, by replacing marine-based ingredients with plant-based ingredients, the presence of anti-nutrients (compounds that reduce nutrients absorption from digestive system) are subject to increase the concentration of pollutants in the farming environment (Table 1) (Davidson et al., 2016; Krogdahl et al., 2010). Therefore, further purification efforts are required in the aquacultures using plant-based aquafeed alternatives to decrease total phosphorus (especially in dissolved form), carbonaceous biochemical oxygen, and total suspended solids. Moreover, replacement of fish meal and fish oil by seafood by-products is expected to increase the aquafeed's ash content (rich with calcium and phosphorus), which eventually causes zinc deficiency in aquatic species (Naylor et al., 2009; Shearer and Hardy, 1987). Therefore, implementation of zinc elevation steps is required in aquacultures using seafood by-products to mitigate the reductions in species growth and other performance characteristics (Song et al., 2017). Investigation of the economic challenges that the aquaculture industry is facing is another point of critical concern. High sensitivity of aquacultures' net revenue to the products' retail price is elaborated on previous studies (Xie and Rosentrater, 2015; Quagrainie et al., 2018). Therefore, running aquaculture systems with the optimized operating costs (including the feeding diet) to ensure positive net revenue at varying products' retail prices is an important area of consideration in future. Future studies could conduct further investigations on methods and strategies to overcome practical seafood production challenges using fish meal free and fish oil free alternatives.

4.3. Other promising alternatives

There are a variety of other promising alternatives that have been reported in the literature to potentially lead to more sustainable aquafeeds (Pelletier et al., 2018). These alternatives include krill, feather meal, and insect-based meal (e.g. soldier fly and house fly larvae). Krill is reported to be the most "underutilized" marine-based resource (due to cost and regulatory restrictions) (Naylor et al., 2009, Tou et al., 2007), that has the potential to be a high-quality protein resource (Landymore et al., 2019, Katevas, 2014). Feather meal, which is a co-product of poultry processing (Campos et al., 2017), is reported to propose a high crude protein content (~86%) (Pelletier et al., 2018, Jasour et al., 2017). Black soldier fly and house-fly larvae is reported to be another highly promising alternative to provide sustainable protein, following the industrial ecology concept (feeding input from the growing animal agriculture waste) (Pelletier et al., 2018, Stull and Patz, 2019, Magalhães et al., 2017). Despite the inherent capability of these alternatives to fully or partly replace fish meal and fish oil in aquafeeds formulations, further research is required to understand (a) the required essential and semi-essential supplements that need to be integrated with the alternatives to obtain the optimized results in terms of products' quality and sustainability, and (b) the scale-up barriers for industrial aquafeeds production using the alternatives (Pelletier et al., 2018).

5. Conclusion

As current trends show an increasing desire towards aquafeeds production with the omission of ocean-based resources use (fish meal and fish oil), the present paper focuses on providing a broader perspective on fish meal and fish oil replacement strategies, considering a wide variety of relevant environmental indicators (impact categories).

A comprehensive analysis of the environmental impacts of aquafeed production is performed on 12 practically formulated and tested aquafeeds with different ingredient compositions, including fish meal and oil free diets. As the investigated diets have already been successfully utilized, their practicality is assumed to be promised. However, the environmental implications of investigated aquafeeds have been different in terms of resources use and pollutant emissions.

The major findings of this study are:

- Ø Sole replacement of fish meal (no fish oil replacement) is potentially not effective enough to significantly reduce the use of biotic resources, but the replaced ingredients (poultry meal, soybean meal, and fish trimming by-product) can potentially lower the impacts based on other emission-based and resource-based indicators.
- Ø Sole replacement of fish oil (no fish meal replacement) can potentially lead to significant decrease in the use of biotic resources. However, technologies regarding substitution methods needs to be improved in order to mitigate the energy use and its associated environmental impacts.
- Ø In order to mitigate the overall environmental impacts of aquafeed production, considering biotic resources, abiotic resources and pollutant emissions, energy-efficient fish oil replacement strategies should be applied in addition to the fish meal replacement by alternatives with lower conventional environmental impacts.

Author credit

Both authors participated in the paper fully. RG and AH designed the modeling, RG performed the modeling and wrote the paper, while AH edited the paper and gave feedback.

Declaration of Competing Interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2020.104849.

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