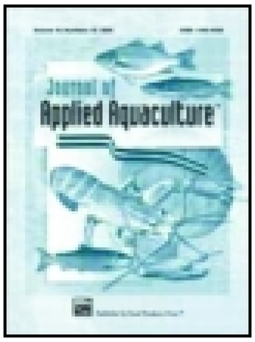

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Review of applying material flow analysis-based studies for a sustainable Norwegian Salmon aquaculture industry

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ABSTRACT

Since its beginning in the early 70thies, the fast growing Atlantic salmon aquaculture industry in Norway has been and still is an object for research across numerous disciplines and research fields. This article presents an overview of the research studies applying Material Flow Analysis (MFA) based methods on Norwegian Aquaculture of Atlantic Salmon starting from 2004 until 2018. The studies were reviewed in relation to their applied method, involved institutions, flows, data acquisition, and suggestions for improvement. All of the reviewed studies applied different MFA methods suitable to the objective of each study, were done with involvement of multiple institutions and stakeholders, modeled credible data and provided specific suggestions for reducing the environmental impacts and optimizing nutrients utilization efficiency. The review concludes that MFA-based methods have the potential for having a functional role within the framework of the Norwegian Salmon Aquaculture industry's sustainable development. A key factor in fulfilling that potential would be diversifying the objectives of MFA research to be more inclusive of the three pillars of sustainability: environment, economy, and society.

KEYWORDS

Salmon; material flow analysis; aquaculture; sustainable development; Norway

Introduction

Background

Today, aquaculture is a major global supplier for seafood, a significant contributor to the human food security and the fastest growing food production sector in the world (FAO 2018). United nation's food and agriculture organization reported that the total aquaculture production is representing about 53% of the total seafood production in the world, and it is continuously growing in contrast to the wild capture fisheries production that remains almost the same for the last 30 years (FAO 2016). Norway is globally ranked second major exporter of fish and seafood products to the global market (FAO 2018). Aquaculture of Atlantic salmon (*Salmo salar*) in Norway is a significant contributor to the economy; in

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2016 it made a total export revenue of NOK 61.5 billion as mentioned in the Norwegian aquaculture analysis report (Ernst&Young 2017).

Aquaculture is a rapidly growing food production sector exploiting ecological resources. The major challenges facing the Norwegian salmon farming sector are: reduction of fish escape to the wild, combating infection with sea lice, reduction of water pollution, implementing regulations(Bergheim 2012). Salmon aquaculture in Norway is relying on imported feed ingredients from South America (Ytrestøyl, Aas, and Asgard 2015). The long supply chain of feed ingredients increases the cumulative energy costs and environmental footprint of this industry. Norway is committed toward sustainability and environmental footprint reduction of all its industries and officially engaged in several international agreements through the Kyoto protocol and Paris agreement. The growing trend of preferences among consumers worldwide for a food product with minimum adverse effects on the Environment (de Boer 2003) requires more research for assessing the environmental impacts of salmon aquaculture. Norwegian salmon aquaculture production is considered as having a lesser impact on the environment compared to salmon farming in other countries (Pelletier et al. 2009). Aquaculture feed material global consumption in 2008 was 30 million tons and expected to grow to reach around 71 million tons in 2020 (Tacon, Hasan, and Metian 2011). The rapidly growing demand for fish feed demands an efficient use of feed material and optimizing the feed conversion rate. Research sponsored by the Norwegian government assists the industry to face up to its challenges and limitations. (Asche et al., 1999; Chu et al. 2010).

Aquaculture research and sustainable development; Norwegian perspectives

The aquaculture production sector in Norway aims at profitability, competitiveness and sustainable development (Aquaculture-Act 2005). This developmental strategy for the salmon aquaculture industry in Norway is underpinned by a governmentally prioritized and supported scientific research (Strategy 2007). In addition, the Norwegian stand on development is guided by a national agenda that takes objectives from the global vision of 2030 Agenda for Sustainable Development Goals (SDGs). Norway's follow-up on Agenda 2030 for sustainable development goals is committed to work with international organizations to preserve the oceans as a global sustainable resource (Ministries 2016). Based on that commitment to these global visions for sustainable development, Norwegian institutions contributes their share to FAO's development of norms & standards for sustainable aquaculture management (Report 2017). Norwegian aquaculture industry and research institutions adopted the global sustainability goals and their measurable targets as part of the aquaculture sustainable development strategy. Material flow analysis (MFA) methodology was applied to evaluate the sustainability of salmon aquaculture production system in order to define measures that will improve its efficiency.

The MFA methodology

Material flow analysis (**MFA**) was developed as a systematic assessment of the flows and stocks of materials within a defined system (Brunner and Rechberger 2005). MFA is a broad concept and a family of methods (Balat 2004). The methods differ according to their purpose, system boundaries and the modeling of material flows within an entity or sub-entity; whether its goods, substances or nutrients. Substance flow analysis method **(SFA)** deals exclusively with identical units of matter homogeneous in qualities. Another MFA method is the Life Cycle Assessment **(LCA)**: a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy with the associated environmental impacts directly attributable to a product or service system throughout its life cycle. LCA has a documented standardized technical framework laid out by the International Organization for Standardization (ISO 2006). MFA-based methods have been applied on different production systems and they had proven capacity to generate information on resources, environmental pollution and waste material (Binder, van der Voet, and Rosselot 2009).

The role of MFA methods in sustainable development was described in four connection points: (1) providing supporting database and information needed to formulate measures to increase the efficiency of waste recycling, reduce resources extraction and emissions; (2) finding out where the losses or inefficient usage of resources happens, identifying key materials or products for environmental policies formulation and sustainable environmental planning and management; (3) defining indicators on the flow of materials for increasing recycling levels and minimizing the wastes, giving direction on the efficient use of resources; (4) increasing the usage of the materials by modeling the socioeconomic responses (Huang et al. 2012).

MFA modeling of a food production and consumption system will assess the economic, environmental consequences, changes in patterns of food consumption and will serve as a practical tool for planning (Risku-Norja and Maenpaa 2007).

LCA was applied on several food products since early 1990s (Andersson, Ohlsson, and Olsson 1994) and later on seafood products (Ziegler et al., 2003) for the purpose of assessing the environmental impacts of the food industry and defining measures to reduce those impacts. Early LCA studies on Aquaculture were published in 2004 by (Papatryphon et al. 2004) and in the same year in Norway (Ministers 2004). However, even though MFA-based methods have shown promising results, there are some limitations and common critiques, mainly about errors and uncertainties rising from data gaps and lack of knowledge, the degree of data reconciliation, modeling choices and mistakes, non-verified imputations and variations between different measurement methods (Patrício et al. 2015). The most significant limitation is attributable to the fact that MFA depends less on empirical observation but rather on collective social constructed knowledge (Meylan et al. 2017). The reliability of the MFA outcomes is dependent on the quality of the used data. The sources of the secondary data used in the MFA model might be to a certain extent an indicator on the data truthfulness, accuracy and relevance.

Review method

Number of peer-reviewed journal papers and official institutional reports concerning MFA-based studies on Norwegian salmon aquaculture were reviewed. The main aim is to identify trends and directions in the research related to the Norwegian salmon aquaculture industry as well as the MFA methodology and resulting suggestions for sustainable development of this sector. The orientation of this study lies within the systematic literature review methodology.

The literature search were limited to peer-reviewed journal articles and official institutional reports. The basis for the literature search was the Web of Science online database (http://webofknowledge.com), and Scopus (https://www.scopus.com), using following keyword: Norway, salmon, aquaculture, and one of the terms LCA, LCS, MFA, SFA, and NFA. In addition, the same keywords were entered in to the search engine Google Scholar (https://scholar.google.com), in order to crosscheck the findings and broaden the search.

The selection of the studies was according to several integrated criteria:

(1) It is a MFA-based study.
(2) It is an aquaculture production system for Atlantic salmon (*Salmo Salar*).
(3) It illustrates applicable suggestions for sustainable development.
(4) It is applied on a Norwegian production system.

Selection on these criteria retained 16 papers.

The overreaching research questions guiding this literature review study where:

- what are the overall sustainability objectives in MFA-based research studies in the Norwegian salmon aquaculture industry?
- what elements shaped the context of the reviewed studies for instance, namely, the involved institutions and stakeholders, sources for data and information and the directed motive for sustainability?
- what are the main areas of improvement identified on the strength of the outcomes of the reviewed MFA-based studies conducted on the Norwegian salmon aquaculture industry to make it more sustainable?

A preliminary systematic analysis of the selected body of literature indicated as important factors: applied method, study's objectives, investigated materials, data acquisition and the outcoming suggestions for improvement categorized and discussed. These factors guided the review described here-under and illustrated in Figure 1.

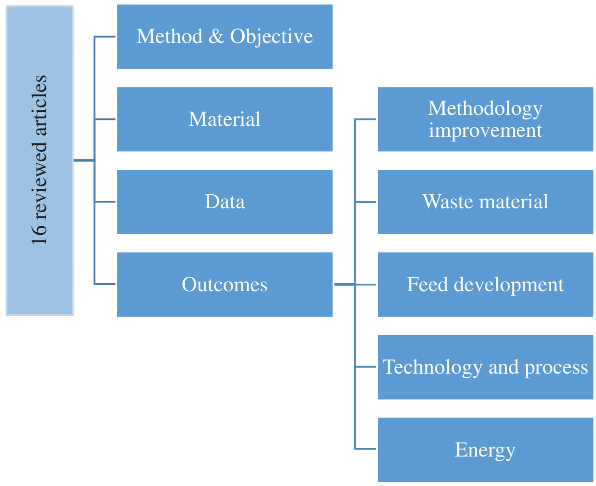

Figure 1. Review structure: The retained 16 studies reviewed according to this structure.

Discussion of findings

The selected MFA studies were expanding from 2018 on backward with no findings earlier than 2004. The general context in the reviewed MFA studies is seeking sustainability in Salmon farming mainly through reducing the ecological impacts and increasing the system's efficiency. Norwegian governmental leadership role in aquaculture research and development is significant and motivated for addressing relevant environmental issues (Chu et al. 2010). The global agenda for sustainability is taking part in shaping the context of the reviewed studies and contributing to their content. International organizations like FAO-UN with its reports are commonly referred to as source for information and the IFFO organization its data, statistics, and the international standards organization for its ISO 1440 standard for the LCA method. A detailed look at the reviewed studies revealed patterns and interrelations between the studies objectives, methods, data sources, and the context of turning this industry to a more sustainable production sector is socially and governmentally driven.

The applied methods and studies objectives

The reviewed studies developed structured systematic models based on quantifying the material flow in the system. Researchers analyzed and discussed those models according to the stated objective of each study. Table 1 summarizes the reviewed studies according to the applied method and its objective. Twelve of the 16 reviewed studies were applying LCA method with environmental impacts. Moreover, LCA standard method include a final interpretation phase to identify conclusive well-substantiated findings to lower the environmental impacts of the assessed system. Only few research papers were dealing with

Table 1. The methods applied in the selected studies.

Author & year	Method	Objective of the study
Ministers (2004)	LCA	Introduce LCA as an environmental assessment method for Nordic seafood products.
Ellingsen and Aanondsen (2006)	LCS	Assess environmental impacts of Salmon farming in comparison with chicken and cod from capture fisheries.
Ellingsen, Olaussen, and Utne (2009)	LCA&LCS	Seafood-oriented environmental analysis, preliminary study of CO_2 emissions from Norwegian farmed salmon.
Winther et al. (2009)	LCA	Quantifying carbon footprint and energy use of Norwegian seafood products including improvement options
Boissy et al. (2011)	LCA	Assess environmental impact of marine ingredients with plant ingredients in Salmonid feed.
Hognes, Sund, and Ziegler (2011)	LCA	Carbon footprint and area required to produce 1 kg of Norwegian salmon.
Torrissen et al. (2011)	LCA	Sustainability of salmon aquaculture production.
Ytrestøyl et al. (2011)	LCA	LCA for resource utilization and eco-efficiency of salmon farming in Norway
Ford et al. (2012)	LCA	Identifying local ecological impacts of salmon farming.
Hognes et al. (2012)	LCA	To map the environmental hotspots in the farmed salmon production system.
Ziegler et al. (2013)	LCA	Carbon footprint evaluation in comparison with other seafood products
Ytrestøyl, Aas, and Asgard (2015)	NFA	Farmed salmon nutrients retention, and feed marine ingredients utilization.
Cashion et al. (2016)	LCA	LCA method improvement concerning marine resources usage.
Hamilton et al. (2016)	SFA	Holistic mapping for the flow of phosphorous in the sectors of aquaculture, agriculture and fisheries.
Aas and Åsgård (2017)	NFA	Nutrients and energy content of feed spills and fish feces (sludge) of salmon farming in Norway
Philis et al. (2018)	SFA&MFA	Energy and phosphorous consumption comparison between using seaweed vs. soya protein for salmon feed

nutrient-substances, despite the fact that salmon farming pertains to the food production sector.

For the first nine consecutive years, MFA application was limited to LCA, a steady trend initiated in the earliest study found. This study was a project of the Nordic Council of Ministers that stands as a milestone as the methodology of LCA for environmental impacts assessment of aquaculture was presented, discussed and method adopted (Ministers 2004).

First nutrient flow analysis (NFA) study (Ytrestøyl, Aas, and Asgard 2015) included in NOFIMA (Norwegian governmental research institution) report investigated the flow of nutrients like: protein, lipids, omega 3 within farmed salmon production system and the efficiency of their utilization. Two years later NFA study targeted the feed spill, i.e. uneaten feed and the salmon fish feces ending up as bottom sludge with a significant content of nutrients and energy as waste (Aas and Åsgård 2017). The study discussed potential improvements to reduce this loss and importance of choosing NFA method for modeling the nutrients flow within the system. The MFA methods were frequently used for comparison purposes, for example, Ellingsen and Aanondsen (2006) conducted a comparative LCA study of the environmental impacts of Norwegian cod fishing, Norwegian salmon aquaculture and Norwegian chicken farming for meat. The study aimed at defining references for comparison and areas for potential improvement with respect to environmental performance. Boissy et al. (2011) published an LCA study to compare the ecological impacts of plant-based feed for farmed salmon vs. a standard feed made with fishmeal and fish oil ingredients. Philis et al. (2018) did MFA/SFA study to compare the phosphorus and energy consumption between using seaweed protein vs. soybean protein as feed ingredients for salmon aquaculture. One of the common objectives of the LCA studies is methodology development. Cashion et al. (2016) reviewed several LCA studies and suggested a modification of the method; specifically the calculation of the primary production rate. The study demonstrated the suggested modification by applying it on a model of the marine-derived inputs in Norwegian salmon aquaculture feed production. Another LCA study defined new local potential environmental indicators for all the production stages of salmon farming, proposed them to be included in future LCA studies (Ford et al. 2012).

Application of SFA method targeting a specific substance flowing through the Norwegian salmon aquaculture system is relatively recent. A landmark SFA study targeted phosphorous flow in Norway done by researchers at the Norwegian university of science and technology (NTNU). The study came up with a holistic model that integrated the sectors of aquaculture, fisheries, and agriculture aiming toward a multiple systems-wide phosphorus management by identifying the inter-sectoral synergies (Hamilton et al. 2016). Two years later, in 2018, another SFA study was done in the same institution (NTNU) and SFA was applied for comparison between two feed ingredients as alternatives to each other (Philis et al. 2018).

The timeline of the reviewed studies in Table 2 reflects the trend in the study objectives to become more specific to details and more diverse with methods, clearly due to the accumulation of published knowledge and the academic direction toward investigating further areas.

Targeted materials and substances

The studies discussed the flow of material and substances within the salmon farming industry. Each study defined certain material or substance to trace according to the scope and objective of the study. Substances like: phosphorous, nitrogen, omega-3, fatty acids of DHA, EPA, pigments (astaxanthin) were present in the reviewed studies. Goods and materials like: salmon feed mix (feed pellets); plant-feed ingredients, fish oil, rapeseed oil, soya beans protein concentrate, fishmeal, seaweed protein concentrate, fish scrap, sludge, and the Salmon fillet product were studied and their quantified flow was modeled and analyzed. No studies found targeting any material nor substances outside from

Table 2. Categories of out coming suggestions for salmon farming sustainable development.

Author & year	MFA method	Methodology improvement	Technology & process	Energy	Waste & nutrients recovery	Feed development
(Ministers 2004)	LCA	X				
(Ellingsen and Aanondsen 2006)	LCS			X		
(Ellingsen, Olaussen, and Utne 2009)	LCA&LCS	X				
(Winther et al. 2009)	LCA	X				
(Boissy et al. 2011)	LCA	X				X
(Hognes, Sund, and Ziegler 2011)	LCA	X				X
(Torrissen et al. 2011)	LCA		X			X
(Ytrestøyl et al. 2011)	LCA			X		X
(Ford et al. 2012)	LCA	X				
(Hognes et al. 2012)	LCA	X				X
(Ziegler et al. 2013)	LCA	X		X	X	
(Ytrestøyl, Aas, and Asgard 2015)	NFA	X	X		X	X
(Cashion et al. 2016)	LCA	X				
(Hamilton et al. 2016)	SFA	X			X	
(Aas and Åsgård 2017)	NFA		X		X	
(Philis et al. 2018)	SFA&MFA			X		X

the food chain, for example, any specific chemical contaminants, pesticides, herbicides, antibiotics or heavy metals that could possibly exist within the salmon farming value chain.

Data sources and quality

The reviewed studies used data obtained from multiple sources. By looking into the data acquisition and the sources of the used secondary data, this study is pointing out to the issues of data credibility, accuracy, and relevance. The studies acknowledged several national highly credible institutions for providing material inventory lists, statistics and results for the research. Such institutions are valid sources for information. The studies about salmon feed material and its composing nutrients relied heavily on data and information from the private sector feed manufacturers who are well established in the market as large-scale corporate suppliers, a sign of cooperation and involvement of a major stakeholder in the development of the Aquaculture industry in Norway. Data regarding imported plant-feed ingredients like soya beans were collected from lists published by international organizations like UN-FAO, Marine ingredients international organization (www.iffo.net), and from the major corporate suppliers in the market. The data were processed and modeled accordingly. However, the variability of data sources were each parameter comes with a level of uncertainty will lead to accumulative uncertainty in the final model (Philis et al. 2018). From early reports, it was stated that the method is limited by an extensive uncertainty due to a lack of data on certain parts of the system (Ministers 2004).

For example, the lack of sufficient data about food processing and post-consumer food wastes (Hamilton et al. 2016), the absence of sufficient data on the nutrients composition, as not all feed ingredients have been analyzed to their content of substances; in this case, the developed models are partly based on estimated values (Ytrestøyl, Aas, and Asgard 2015). All these shortcomings contribute to the uncertainty of the conclusions on these assessments. Five studies out of sixteen obtained primary data, one used chemical analysis, and the other four used direct correspondence and interviews. Besides the issues of data insufficiency and data gaps, the quality and accuracy of the available data is a legitimate question. There is an absence of a standard verification protocol for the secondary data, either by chemical analysis for samples or to be crosschecked with data from another source. Significant points raised in the reviewed studies regarding data statistical reconciliation and error propagation analysis (Cashion et al. 2016). For data processing and modeling the reviewed studies relied on computer software; Microsoft Excel for primary processing followed by secondary processing and modeling using SimaPro for LCA studies, STAN for SFA study (Hamilton et al. 2016) and eSankey for SFA/MFA study (Philis et al. 2018).

Outcomes

All of the 16 studies reviewed gave suggestions for efficiency improvements and sustainable development based on the outcome of each study. The suggestions were grouped within following categories: improvement of methodology, technology and process, energy, waste & nutrients recovery and feed improvement, summarized in Table 2. Some studies came up with suggestion falling under one category, other studies with more suggestions under up to four categories. However, some other general developmental suggestions that do not fall under the categories of Table 2 were briefly discussed; i.e. process management, directing investments, and association with other sectors.

Methodology improvement

Eleven of the 16 reviewed studies suggested modification of the applied MFA method to customize and include technical and environmental criteria. A 2004 report of a Nordic Network project issued/funded by the Nordic Council of Ministers the governments of the 5 Nordic countries took the initiative to conduct the first LCA on the aquaculture industry. Leading to the conclusion: (i) there is a regional strategic vision for aquaculture's sustainable growth and expansion, and (ii) adoption for **LCA** as a standard method for the assessment of aquaculture environmental impacts (Ministers 2004). In a clear trend, nine of the 12 LCA & LCS studies came up with suggestions for the improvement of the method mainly to include local environmental impacts attributed to farmed salmon products in Norway.

Ford et al. (2012) developed indicators of ecological impacts associated with the production stages of salmon farming to be included in life cycle impact assessment (LCIA) of any future LCA study, giving the method grounding in the ecological context. In their LCA report, Hognes et al. (2012) suggested including the feed micro-ingredients for a more accurate total carbon footprint assessment; this is a development on the methodology from previous LCA report done earlier by the same institution (Hognes, Sund, and Ziegler 2011). Cashion et al. (2016) analyzed the use of the primary production required (PPR) in LCA studies as indicator to assess the sustainability of the ecosystems where salmon feed marine ingredients are harvested from. Suggesting a more refined method that considers the specific species harvested for fishmeal and oil yields, the source ecosystem-specific transfer efficiencies and results expression as percentage of total ecosystem production. The modification was demonstrated through a comparison of results before and after applying this methodological improvement.

Nutrient flow analysis (NFA) study discussed the most suitable MFA method to evaluate the sustainability of the salmon farming system and reached a highlighted conclusion that it would be SFA or NFA rather than LCA. The commonly used functional unit of weight and mass balance in LCA method does not reflect the qualitative change in the nutrients content that the process is causing. The study recommended including the retail chain in the boundaries of assessing this production system because most of the food waste take place after the product departs the farm gate, assessment of the retail product-handling practices might be justifiable. SFA study targeting phosphorous assured on the importance of locating the spatial and temporal distribution of the targeted indicator substance. Consideration that practically raised the methodology above its typical application on a single sector, and tracing the substance to other sectors. Expanding the modeled system boundaries over multiple sectors of aquaculture, fisheries and agriculture lead to defining the phosphorous flow linkages and synergies between the different sectors revealing potentials for tradeoffs (Hamilton et al. 2016).

Technology & process

Three studies pointed toward the need for technological improvements on the equipment to account for losses in material. The **NFA** Study by Ytrestøyl, Aas, and Asgard (2015) discussed the loss of nitrogen and phosphorous due to uneaten feed and how it is affecting the marine ecosystem. The report pointed out the need for further hydrodynamics technological improvements on the feeding systems and the importance of developing better effluent filtration systems as the way to reduce the amount of feed spills. Aas and Åsgård (2017) mentioned the Sludge dewatering technology, sludge treatment, and the need for more efficient feeding systems as technological improvements to optimize nutrients utilization. Nutrients circulation within the system is the parameter to evaluate the performance of the feeding technology, clearly for environmental and economical perspectives. Torrissen et al. (2011) specifically discussed the open cage systems technology for salmon farming and its impacts on the environment and the biodiversity making an informed call for the improvement of the process toward better control over the flowing out feed spills and escaped fish.

Energy

The energy consumption, the associated carbon footprint, and their reduction were targeted and discussed in four reviewed studies. To lower the carbon footprint of the product they suggested for instance, the use of hydropower, largely available in Norway; the use of heat generated by incineration plant to compound feed (Philis et al. 2018). The carbon footprint of the salmon aquaculture production system is mainly determined by the quantity and type of the feed ingredients (Ziegler et al. 2013). Other researchers looked into aquaculture's associated cold transportation; favored liquid natural gas as more efficient fuel over diesel, uses of the sludge for the production of methane as a source of energy (biogas). The modeling of the materials flowing in and out of the system and the quantification of its carbon footprint discussed alternatives and tradeoffs.

Waste and nutrients utilization

In four studies, the flow of the salmon feed material was modeled. The nutrient balance of macro-nutrients and micro-nutrients within the production system, i.e. the amount fed, retained, excreted, wasted, is assessed. The SINTEF report 2012 mentioned the extraction of fish oil out of salmon by-products at the rate of 9% as given by Hordafor (private sector Norwegian feed ingredients producing company); raising the question if this form of extraction is applied in all salmon post-harvest processing factories. Nutrients loss is associated with ecological problem of eutrophication; that appeared clearly in different LCA studies. NOFIMA a research institute funded by the Norwegian government reported in 2017 the quantity of 11,251.142 tons of dry matter sludge coming off the Salmon Aquaculture production in Norway. The sludge came mainly from feed spills and fish-feces. The lack of utilization of the sludge as a source of nutrients makes the system distant from being a closed-loop materials cycle by the industrial ecology's definition, the report clearly provides suggestions for improvement starting from increasing the digestibility of the feed suggesting a detailed amendment of removing indigestible carbohydrates as a recommendation for the feed manufacturers. However, the report stressed developing the feed system, effluent collecting, and sludge dewatering and filtration technology. A model for minimizing the losses of phosphorus has been established (Hamilton et al. 2016) phosphorous is a valuable micro-nutrient.

Feed development

Seven studies modeled the material flow in and out the system, quantified the environmental effects; for the objective of defining alternatives to develop the salmon feed. Studies were able to present numerical data favoring certain alternative ingredients with less environmental impacts plant-based ingredients were suggested to replace fish oil and fish meal as an alternative with lower environmental impact (Boissy et al. 2011). A study discussed several feed ingredients, including resource intensive agricultural inputs such as soy, sunflower meal, wheat and corn gluten considering their growing, transport and processing energy costs; they might not have a lower carbon footprint than their marine substitutes (Hognes, Sund, and Ziegler 2011). The environmental costs of the micro-ingredients, and the freshwater footprint of the plant ingredients are brought to the discussion as considerable factors (Hognes et al. 2012). A study found that using marine ingredients for salmon feed is more sustainable option if fishmeal is produced from seafood processing byproducts and from well-managed small pelagic fisheries (Torrissen et al. 2011). (Ytrestøyl et al. 2011) raised questions regarding the most efficient route for the flowing nutrients within the salmon industry. The frequently acknowledged involvement of the major feed manufacturers in Norway in providing their data for the reviewed studies reveals a level of cooperation between research and industry.

Conclusions

There is a clear role for the MFA-based methods as a tool to develop specific objectives for a more sustainable Aquaculture Salmon production in Norway. The reviewed studies provided a quantified outcome that is supporting applicable measures on specific areas that are in need for further improvement. The MFA-based studies conducted in Norway between 2004 and 2018 came up with suggestions and considerations in the areas of lowering the environmental impacts, feed development and improving efficiency of nutrients utilization. Significant contribution to the systems information pool and guiding knowledge. However, applying the MFA methodology to address specific objectives relevant to fish post-harvest processing and optimum nutrients extraction was not at the center so far with a dominance of the environmental objectives. This could be a fertile area for future MFA research; were food security and minimizing post-harvest processing food loss are the main objectives. Several studies fall in a steady trend to customize the MFA-based methods to fit the local context and face up its requirements.

This review remarks the diverse involvement of multiple stakeholders and contributors in the reviewed MFA-based studies, involvement that can be described as a structural framework for the ongoing research and development of the salmon aquaculture production sector in Norway.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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