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Conceptualization of the Norwegian feed system of farmed Atlantic salmon

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The total production of Norwegian Atlantic salmon is expected to increase considerably in the years to come. A majority of greenhouse gas emissions from aquaculture is accounted for by feed. To investigate and assess the sustainability and robustness of the feed system, a holistic perspective on the system is needed. We aim to conceptualize the current value chains of feed in Norway using the Food Systems Approach, existing literature, and stakeholder inputs. The Sustainable Development Goals include no specific mention of feed. Still, many Norwegian feed and animal producers link their sustainability work to these goals. This paper summarizes the sustainability perspectives of feed and animal producers in the aquaculture sector, as well as relevant background, regulations, and environmental and socio-economic drivers.

KEYWORDS

food systems approach, sustainability, feed value chain, aquaculture, customer characteristics

1 Introduction

Atlantic salmon (*Salmo Salar*) is one of the most important export commodities in Norway, and future growth in the industry is expected (PwC, 2023). A majority of the carbon footprint of the salmon from farm to harvest is accounted for by the feed (Ziegler et al., 2021). Feed for salmon produced in Norway has global and complex supply chains, and in 2020, 92% of the feed ingredients were imported (Aas et al., 2022). These supply chains can be vulnerable to political shifts, epidemics as well as climate change, which has been observed more often in the last years (Free and Hecimovic, 2021). To reduce the dependency of imports and vulnerable supply chains, Norway has developed a goal to increase the self-sufficiency (Regjeringen, 2021), and domestic production of sustainable feed resources for fish feed can contribute to this.

To investigate and assess the sustainability and robustness of the feed system, a holistic perspective on the system is needed. The aim of this work is to conceptualize the current value chain for feed for Norwegian produced salmon. This is performed by creating a conceptual model of the Norwegian feed system following the Food Systems Approach (FSA) (Van Berkum et al., 2018). FSA is a conceptual, interdisciplinary framework based on systems thinking. This method enables us to have a better understanding of the feed system with focus on salmon aquaculture and identify current challenges and opportunities in a shift towards new and Norwegian produced feed ingredients.

2 Methodology

Based on the FSA framework (Van Berkum et al., 2018), the main elements and drivers of the Norwegian feed system for the grow-out phase for Norwegian salmon aquaculture are identified through existing literature, including journal articles, research reports, company reports and web pages. The components of the Norwegian feed system activities include the supply chain, enabling environment (e.g., regulations, policies etc.), customer characteristics, service industries, environmental and socio-economic drivers and how these interact with each other. A conceptual model was created based on the FSA, shown in Figure 1.

An FSA has several benefits as a framework to assess the food system (Van Berkum et al., 2018). The approach provides a checklist of topics to address when assessing the system that enables the user to identify relationships, root causes and feedback loops in the system. Also, it can help understand and map the environmental and socio-economic impacts as well as determine limiting factors for achieving food security. The framework shows where main interactions and feedback of subsystems are occurring. This can lead to insights on how to use natural resources more efficiently, what potential trade-offs exist, and the implications of the food system on food security, society and environment (United Nations Environment Programme, I. R. P, 2016). Using the FSA also enables comparison between different food systems, such as different types of animal production, or for salmon production in other countries such as Chile, Scotland and Canada, compared to Norway.

Within customer characteristics, the focus is on two links of the supply chain: feed producers and salmon farming companies. To assess this, literature and company reports are reviewed to identify what feed and salmon producers highlight in terms of sustainability. Within enabling environment, the Norwegian regulations regarding feed, and policies are mapped using reviews of document of statutory requirements for feed. Environmental and socio-economic drivers are summarized as examples of relevant impact factors for the relevant value chain. End consumers habits and perception towards consuming seafood are also mapped, based on national surveys and available literature.

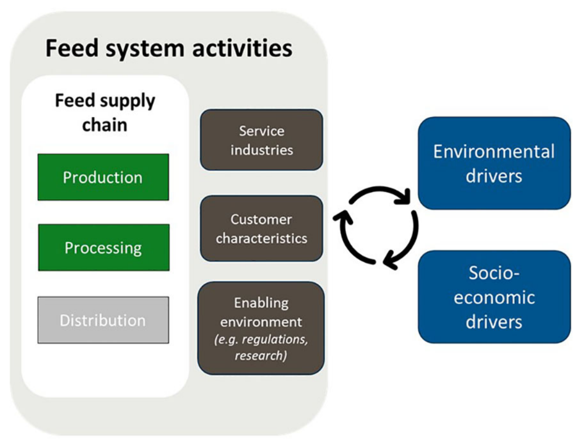

FIGURE 1
A conceptual model of the feed system activities and affecting drivers, based on the food systems approach (Van Berkum et al., 2018).

As part of mapping the supply chain, the material flows of feed for grow-out production of salmon until edible product are quantified for 2020. The feed composition is based on Aas et al. (2022). Total amounts of feed used and production volume are taken from the Directorate of Fisheries (Fiskeridirektoratet 2023c, 2023a). It is estimated that the edible part of salmon is 53% based on round weight (Carvajal et al., 2021). Round weight is approximately 93.7% of the live weight of salmon (Fiskeridirektoratet, 2023b). The round weight is the weight of salmon after it is starved before slaughter and after the blood is removed (Norsk standard, 2012). 47% of the round weight is regarded as rest raw materials (RRM). RRM refer to the parts that do not go to human consumption, such as head, blood, bones, viscera etc (Myhre et al., 2023). However, this is specific for the Norwegian market, as consumers in other countries might have a higher or lower degree of utilization, e.g. in Norway it is not common to eat fish heads, but this is common in other markets. The quantification is visualized with Sankey diagrams using the Plotly package in Python (Plotly Graphing Libraries, n.d).

3 Feed supply chain of salmon aquaculture production in Norway

This section addresses the supply chain of feed in Norway and describes the composition of feed as well as origins of the feed ingredients. We further investigate the production of salmon and shares of edible parts and RRM. The feed use and salmon production has been quantified and is presented in Figure 2.

Total feed used for grow-out fish production was 1.87 million tons in 2020 (Fiskeridirektoratet, 2023a). The feed composition in 2020 consisted of about 22% marine ingredients, 73% plant based and includes 0.4% of insects, microalgae, single cell protein and fermented products (Aas et al., 2022). In total, 92% of the ingredients were imported, including all volumes of plant-based ingredients mainly originating from Europe and Brazil. Only 8% was domestically produced and came from Norwegian fisheries or aquaculture. Another study by Johansen et al. (2022a), report that 38% of the marine oils came from the Northeast Atlantic, 27% from the US, 13% from South America and 0.7% from African sources. 48% of the fish meal sources were also mostly from the Northeast Atlantic. About 30% of fish oils and 33% of fish meal were sourced from off-cuts, while the remaining volume originated from whole fish. Of the plant-based ingredients, soy protein is the dominating ingredient. Johansen et al. (2022a), states that about 81% of the soy protein is sourced from South America, and 19% from Europe and Russia. Rapeseed oil is the most important vegetable oil, with imports from European countries accounting for about 59%,

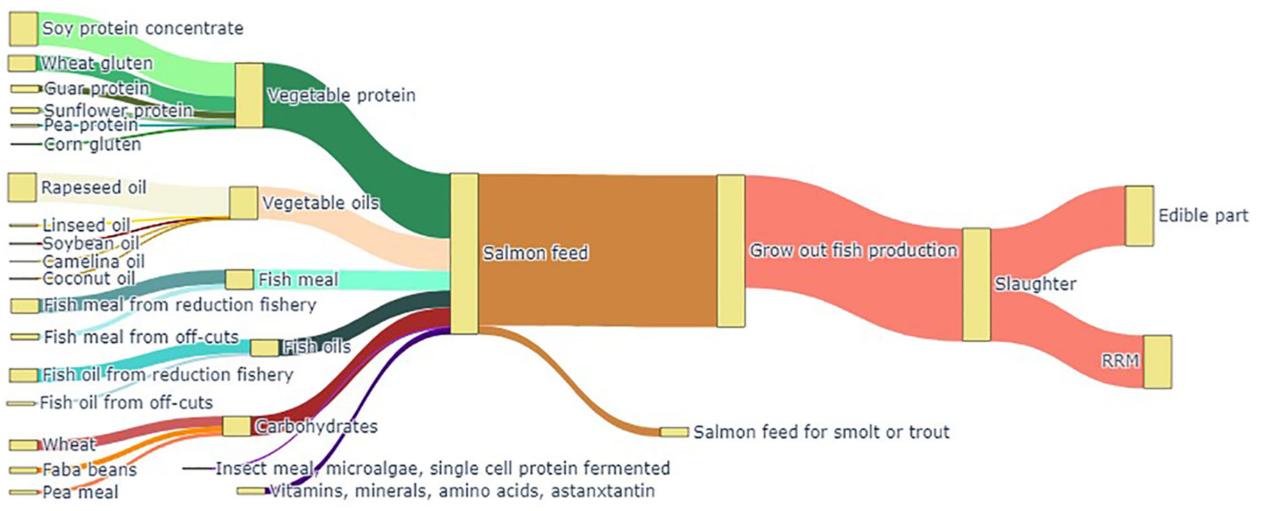

FIGURE 2
Material flows of salmon in 2020, from feed to edible product and rest raw materials (RRM). The figure is based on data extracted from Aas et al. (2022); Fiskeridirektoratet (2023c) and Carvajal et al. (2021). Total feed used for grow-out fish production in 2020 was 1.87 million tons, and 1.39 million tons round weight salmon. This resulted, theoretically, in around 736 000 tons edible product and around 653 000 tons RRM.

followed by about 25% from Russia or Belarus. The composition of salmon feed has changed significantly in the last 30 years from having mostly marine based ingredients to consisting of mainly plant based ingredients (Aas et al., 2019). This is mostly due to decline in the availability of fish oil and meal (Tacon and Metian, 2008; Shepherd and Jackson, 2013; Naylor et al., 2021). The shift to a diet dominated by plant-based oils has also led to a drop in omega-3 content in Norwegian farmed Atlantic salmon (Sissener, 2018).

The marine protein is sourced from wild fish harvested at sea, through extraction of oil at the reduction plant. The remaining mass is dried, milled and processed into fish meal. Off-cuts and by-catch from Norwegian fisheries and aquaculture are also processed into fish meal and oil, commonly used for fish and animal feed. In salmon feed production, the marine and plant-based ingredients are mixed into a company-specific nutritional formula, which varies dependent on the supply of raw materials and the demands of the salmon farmers (Thakur et al., 2020). The feed is then extruded into pellets of a size specific to the development stage of the salmon. According to Thakur et al., 97% of the feed is nationally processed, from ingredients to pellets, and only 3% is imported. Depending on the scale of the customer, the available technology and automation level, the feed is delivered in bulk packaging or pumped in autonomous systems.

In 2022, 1.56 million tons (round weight) of salmon were produced (Fiskeridirektoratet, 2023c). Most of the salmon produced in Norway is being exported as whole fish (head on, gutted). In 2022, about 1.25 million tons of salmon (product weight) were exported, and of this about 995 000 tons were exported as whole, fresh cooled fish (Norwegian Seafood Council, 2023).

In 2022, the amount of available RRM from salmonid aquaculture, including Atlantic salmon and Rainbow trout (*Oncorhynchus mykiss*), amounted to 546 000 tons (Myhre et al., 2023). This includes heads, blood, viscera, skin, slough, bones etc. A lot of the RRM is not available, since the majority of the fish is exported whole. Except for the blood, which accounts for 2% of the total weight of the salmon, all the available RRM was used for extraction of salmon oil to feed, fish protein hydrolysate, fish meal or fish protein concentrate, according to Myhre et al. (2023). About 67% or 218 000 tons of all utilized and processed RRM from fisheries and aquaculture was used for feed applications, with fish feed accounting for the majority.

4 Enabling environment

Norwegian policies and strategies are set in place for the coming years to implement measures to work towards, and achieve, sustainability goals. Even though the United Nations Sustainable Development Goals (SDGs) do not explicitly include feed, feed is an essential part of sustainable development and implemented measures can contribute to achieving several of the SDGs. As stated by Troell et al. (2023), this can create an iterative feedback process where the contributions made to the SDGs in turn influence decision-making and the conditions of the sector. The focus on feed and sustainability has eminently increased recently. In 2022, the Norwegian government announced two new missions to invest in, one of them being sustainable feed (Forskningsrådet, 2023).

There are several Norwegian regulations concerning requirements for feed, from feed materials to production and import. These regulations greatly impact the feed value chain, as the regulations facilitate or disallow the use of different raw materials, countries of origin or processing methods for use in feed. In particular, animal material for use in feed ingredients is covered by specific regulations such as the legislations regarding the use of by-products not intended for human consumption and export of animal by-products to countries outside the European Economic Area (Landbruks- og matdepartementet and Nærings- og fiskeridepartementet, 2016; Helse- og omsorgsdepartementet et al., 2020). For instance, by-products from animals are covered by regulations which divide the material into categories based on the risk they pose, and with stricter requirements for food-producing animals. The use of animal material for feed is also limited by the cannibalism ban, which prohibits feeding a species using processed animal protein from the same species. Using fish meal from wild fish to feed farmed fish of the same species is excepted from this ban (Mattilsynet, 2013), and so are hydrolyzed proteins, which may be used as a feed ingredient for fish feed within the same species (Mattilsynet, 2023).

5 Customer characteristics

Sustainability has become increasingly important in businesses along the entire value chain. The Norwegian regulations cover raw materials allowed for different types of feed and import of feed materials. However, no regulations are set regarding sustainability in the choices made for raw materials in feed mixes. Nevertheless, consumers are becoming more aware of the impact of the everyday choices they make, which encourages companies to operate sustainable in order to be competitive. Still, companies differ in their approach when it comes to dissemination of sustainability work and focus externally. To assess this, websites and reports that are available online are reviewed, to identify what feed and salmon producers highlight in terms of sustainability, and to map the information that is available to the general consumer. The information gathered is therefore not based on reportable information, but rather the information the companies themselves have chosen to share in simplified ways and in open reports to reach a different target group - the general consumer who may be interested in the company's sustainability work. However, in the coming years, more companies will be subject to the European Union Corporate Sustainability Reporting Directive, requiring companies to disclose specific information on the impact of their activities (European Commission, n.d). How this will affect the findings below should be explored further in the years to come.

5.1 Feed producers

Feed is the largest emission contributor when it comes to fish farming in Norway. Thus, it is perhaps not surprising that the feed producing companies have the most thorough sustainability information disseminated through their channels. In addition, demands may be set by the aquaculture companies which lead to the feed companies having such a high focus on the sustainability of feed ingredients, and on communicating this. We have looked at six companies producing feed or feed ingredients for farmed fish, where some are large-scale feed producers, and some are small-scale producers of ingredients to be used in the feed. The larger producers are considered first, and the smaller ones in the last paragraph.

Several of the feed producing companies have separate sustainability reports which focus on important matters from a sustainability perspective. The SDGs appear clearly and consistently in all reports, with a thorough explanation of why each of them is important. Several companies list key performance indicators (KPIs) for various topics with the percentage change from previous years as well as what the target is within a given time. The companies also have focus areas with specific sub KPIs that are measurable. Typical KPIs that are reflected among the companies are water use, energy use, greenhouse gas emissions, and waste management, as well as the use of certified soy and palm oil.

The reports are generally perceived as clear and transparent, and it is easy to find the information you are looking for as well as to see overall what the most important goals and the progress of the companies within a number of topics are. There are, however, some companies that have changed the format of their reports over the years, and have removed several good, clear, and informative solutions in the latest reports, making them more difficult to interpret. The companies are all part of greater initiatives, such as SeaBOS (Seafood Business for Ocean Stewardship), Global Salmon Initiative, Sustainable Fisheries Partnership and ProTerra, where sustainability is a main focus. Several of these initiatives are common among the companies.

Some smaller companies producing ingredients for fish feed have also been looked into. These companies do not have reports but simpler websites containing sections about sustainability, what it means to them and why they contribute to sustainable feed. This also shows how important it is, even for smaller companies, to communicate a clear sustainability focus. Regardless of the company size, all feed producing companies we have looked into use the SDGs as indicators, such as SDG 2 Zero hunger, 12 Responsible consumption and production, 14 Life below water and 15 Life on land.

5.2 Aquaculture producers

We have looked at six aquaculture producers. In similarity to the feed producing companies, the aquaculture companies also have a general sustainability focus which is easy to find in websites and reports. Less often than the feed producers do the aquaculture companies have separate sustainability reports. However, the annual reports have sustainability as central and overarching topics. To find specific information, more navigation through websites and reports is required. Some of the websites have many separate web pages with sustainability information of different and overlapping topics, lacking appropriate search options. In these cases, the information is perceived as unavailable to the consumer, as it is hard to get an overview of the given information, and significantly more work is required than searching for what you are looking for in a single report.

There is little difference among the production companies in the information they provide. Some of the information, however, even in the annual reports, is time consuming to locate. The reports are often substantial, and less graphics are used compared to the reports of feed producers. When searching for specific key words, there are not always (relevant) results, and the key words to look up to find relevant information are not always obvious. All companies refer to the SDGs throughout the documentation they provide and elaborate on key focus areas and targets and how these are achieved. This gives an overview of the available information and a pointer to what topics are considered especially important. Some of the companies also provide specific target values and information of achievement from the last few years for their set indicators, which appears transparent and informative to the reader.

Several KPIs of sustainability work are repeated among the relevant companies, and in particular we have looked at what the companies say regarding sustainable feed. There is a great focus on reducing the environmental footprint from feed. More specifically, the companies aim to do this by introducing new marine ingredients and species, as well as local novel ingredients, in the feed. In addition, increased efficiency of feed consumption and economic feed conversion are mentioned by some as a specific measure to reduce overall footprint of the feed. Despite the goal to source locally, no information was found with any of the individual companies regarding the proportion of Norwegian raw materials in their feed. On the other hand, Aas et al. (2022) reported that the proportion of Norwegian raw material in feed for Norwegian produced salmon in 2020 was only 8%. As the proportion of Norwegian ingredients in the feed is so low, this may be one of the reasons why the companies do not report accurate figures on this in publicly available channels.

5.3 End consumers

The consumption of fish and seafood was between 31-37 kg round weight per person per year between 2003 and 2021 (Helsedirektoratet, 2022). This number includes all species. For fillets, this equals to 13-15 kg per person. The Norwegian Seafood Council has estimated that Norwegians consumed on average 5.63 kg salmon round weight in 2021 (Jensen, 2022).

Most studies on consumer perspectives focus on the end product, the food product consumed, but controversies and critique towards the use of soy in salmon feed and the impact of deforestation of the rain forest in Brazil have been an important factor in making several feed and salmon producers only purchase soy from certified producers (Saue, 2021). Due to both NGOs and consumers becoming more aware of sustainability aspects, it is important to map if consumers will accept novel feed ingredients and even be willing to pay more if they are considered more sustainable. Eidem and Ruud (2022) point out a tendency to eat less of an animal with increased wealth. This means that the RRM ratio increases and less of the animal is used for human consumption, which ultimately reduces the overall resource use efficiency.

Farmed salmon as a source of omega-3 fatty acids has long been an important sales argument (Sprague et al., 2016). As previously noted, the replacement of fish oils to marine oils, has reduced the concentration of omega-3 fatty acids, and increased the levels on omega-6 fatty acids (Sprague et al., 2016; Sissener, 2018), which could overall reduce the health benefits of consuming farmed salmon. On the other hand, a decrease in marine ingredients in the salmon feed has also resulted in lower levels of contaminants such as mercury, arsenic, dioxins, dioxins-like PCBs (Polychlorinated biphenyl) and DDT (Dichlorodiphenyltrichloroethane) in farmed Norwegian salmon between 1999 and 2011 (Nøstbakken et al., 2015). Another study by Lundebye et al. (2017) state that farmed salmon has lower levels of persistent organic pollutants than wild salmon. The levels of omega-3 fatty acids are comparable, but levels of omega-6 fatty acids are higher in farmed salmon. The authors also recommend that the omega-3/omega-6 ratio should not be further decreased as the health benefits of consuming salmon may prevail.

6 Environmental drivers

The FSA divides environmental drivers into six categories, minerals, climate, water, biodiversity, land and soils, and fossil fuels (Van Berkum et al., 2018). These drivers are both impacted by the feed supply chain and vice versa. Life Cycle Assessment has emerged as a common tool to assess the environmental impacts of salmon feed and salmon production (Cashion et al., 2016; Bohnes and Laurent, 2019). Environmental impacts include global warming potential (kg CO_2-eq.), eutrophication potential (kg N or kg P), acidification potential (kg SO_2-eq.). There have been no recent studies assessing all impacts of Norwegian salmon production or salmon feed. However, there has been a series of reports and papers quantifying the carbon footprint of Norwegian salmon (Ziegler et al., 2013; Ziegler et al., 2021; Johansen et al., 2022a).

In 2020, the carbon footprint of salmon at farmgate was approximately 3.8 kg CO_2e/kg live weight (Johansen et al., 2022a). This result includes the impacts from land use change which accounted for 0.8 kg CO_2e/kg live weight salmon. Feed accounted for 75% of the total carbon footprint of the salmon at farmgate including impacts from land use change. The findings of the report state that the use of soy has decreased since 2017 and is sourced from other regions than South America. Soy from Europe and the US have a smaller carbon footprint than soy from South America due to less changes in land use.

Newton and Little (2018) found that for Atlantic Salmon farmed in Scotland in 2018, 90% of all impacts except eutrophication potential was accounted for by the feed, when assessing the impact categories global warming potential, eutrophication potential, ozone depletion potential, acidification potential, water use, land use and photochemical oxidation potential. Eutrophication potential was highest in the farming stage due to nitrogen emissions. Similar results can be expected for salmon produced in Norway, where most of the salmon is farmed in traditional aquaculture production in open net pens, there is usually no collection of sludge, and nutrients and other substances are released directly into the oceans. In 2021 the estimated emissions of phosphorus from aquaculture in Norway was around 15 600 tons (Pandit et al., 2023). A key action to reduce phosphorus emissions from aquaculture is to reduce the phosphorus concentration in the feed using the enzyme phytase, making phosphorus in vegetable sources more digestible for the salmon. The emissions of nitrogen are calculated to be 66 400 tons in 2019 by Broch and Ellingsen (2020). Nitrogen emissions can also be reduced by manipulating the feed composition, and most importantly, avoid feeding the salmon an excess of amino acids (Bureau and Hua, 2010).

7 Socio-economic drivers

The FSA divides socio-economic drivers into five categories, market, policies, science and technology, social organizations and individual factors (Van Berkum et al., 2018). Toussaint et al. (2022) state that social sustainability, in terms of human and labor rights, living conditions and life quality, among other things, are essential to achieve a sustainable food system. Thus, socio-economic drivers can influence, and at the same time be influenced by, the food system as a whole or specific value chains.

The aquaculture sector is economically important in Norway. In 2021, this sector created over 45 000 person-years of employment in the country. Over the last decade, there have been great increases in production value, value creation contribution as well as number of employees in the aquaculture-based supply chain, according to a report from SINTEF (Johansen et al., 2022b).

Resource rent tax on aquaculture has recently been introduced (as of January 1st, 2023) by the government. The tax is on income from the use of natural resources belonging to the state, to ensure the community receives a share of the income created by exploitation of the common resources along the coast. Companies have to pay this as a result of the extra income they get when they are allowed to use a limited resource. This means companies farming salmon, trout, and rainbow trout, and with an income over a certain limit, are taxed at a rate of 40% (Thomassen et al., 2009).

Supply chains and international trade can be vulnerable to global conflicts and events. Sunflower oil and soy are examples of ingredients used salmon feed, and which are imported to Norway (Winther et al., 2020). The soy industry has been reported to cause deforestation, displacement of local peoples and to violate labor rights (Rainforest Foundation Norway and Future in Our Hands, 2018; WWF, n.d). As of September 2023, the ongoing war in Ukraine has greatly affected the world economy. Ukraine and Russia account for 53% of the global production of sunflower oil and seeds. The situation causes reduced trade and increased prices on a number of resources, thus influencing supply chains (Landbruks- og matdepartementet, 2022; Leigland, 2022; NHO, n.d).

8 Conclusion

The Norwegian feed system for aquaculture is a part of a global food system, with significant imports of feed ingredients (92%) and large amounts of exports of salmon. The current feed system and its supply chain are vulnerable to war, conflicts, climate change, extreme weather events and more. Future growth in the industry and reaching the Norwegian government's ambitions to increase the share of Norwegian produced ingredients, will rely on a shift towards new feed ingredients. To ensure the success of new feed ingredients and their sustainability, a thorough understanding of the feed system is required. This paper has highlighted the current status of the feed system, in terms of volumes and composition of feed used, and the produced volumes of salmon. The regulatory environment as well as the characteristics of feed producers, salmon producers and consumers have been mapped.

The composition of salmon feed has undergone great developments from being mostly based on marine ingredients, towards being dominated by plant-based ingredients. This shift has impacted the nutritional composition of the salmon, where levels of omega-3 fatty acids have decreased. This may reduce the overall health benefits of farmed salmon, or at least the reputation of farmed salmon as a source of omega-3 fatty acids. Simultaneously, levels of contaminants have dropped and are currently lower than in wild salmon species.

Differences were observed between the extent of the sustainability focus in producer websites and reports and its attribution among impact categories. Both feed producers and aquaculture companies communicated their sustainability work thoroughly. However, the feed producers were perceived as somewhat more transparent in their dissemination. The research shows that there are variations between the categories along the supply chain when it comes to the sustainability focus. They communicate through websites and reports which are available to the consumer. However, some of the information is not easily accessible and requires extensive searching by the consumer, which could be perceived as less transparent. Nevertheless, there is an increasing focus among companies along the value chains, and many set ambitious goals for the operations going forward, in order to contribute to the mission of increased sustainability. With an increased focus on the topic from regulatory bodies the contributions could be even greater.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

PS: Conceptualization, Writing – original draft, Writing – review & editing, Investigation, Methodology. AS: Conceptualization, Writing – original draft, Writing – review & editing, Investigation, Methodology, Visualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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