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Utilization of feed resources in the production of Atlantic salmon (*Salmo salar*) in Norway: An update for 2020

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ABSTRACT

The utilization of feed resources in Norwegian salmon farming has previously been reported for 2010, 2012 and 2016. This paper presents an update for 2020, giving an overview of the feed ingredients used and retention of nutrients in fillet and whole salmon for the entire Norwegian salmon production.

A total of 1,976,709 tonnes of feed ingredients were used to produce 1,467,655 tonnes of salmon. The feed was produced from 22.4 % marine ingredients, 73.1 % vegetable ingredients and 4.1 % micro ingredients such as vitamin and mineral premixes, astaxanthin and crystalline amino acids. In addition, 0.4 %, or 8126 tonnes, of single cell protein, insect meal, fermented products and microalgae were used in salmon feeds. Norwegian marine protein and marine oil constituted 8.3 % of the ingredients. The remaining 91.7 % of the ingredients were imported. The feed conversion factor was 1.35 if calculated from feed ingredients 'as is', or 1.25 if calculated form ingredients on dry matter basis. The retention of energy, dry matter, protein, fat, EPA + DHA and phosphorus from feed was 39 %, 33 %, 34 %, 57 %, 49 % and 25 %, respectively, in whole salmon. In fillet, the corresponding retention rates were 25 %, 21 %, 25 %, 35 %, 32 % and 12 %, respectively.

The feed ingredients used and the utilization of feed in 2020 resembled that of 2016, except that there was an increase in the amount produced in 2020 and a slight increase in the economic feed conversion ratio (eFCR).

1. Introduction

The salmon farming in Norway, as the world aquaculture production (FAO, 2020), is increasing and expected to increase further. Feed is the number one economic and environmental input factor in salmon farming. Efficient utilization of the feed is important, both economically, and in a sustainability perspective. The major proportion of the energy consumption, and, thus, release of climate gases is related to the production of salmon feed (Newton and Little, 2018). But the percent of energy attributed to feed is not alone descriptive of the sustainability of the salmon farming or other animal farming. On the contrary, if the use of feed in salmon farming remains constant, the per cent of energy related to feed will increase if energy used for transport and other farming operations is reduced.

Salmon feed is energy- and nutrient dense. It must cover the salmon's nutritional requirements, physical properties must be suitable for the fish and the logistic system, economic sustainability is a prerequisite, and the demand for environmental sustainability of the feed is increasing. The feed is produced from high quality ingredients traded in a global market. Which ingredients are used, how they are sourced, and the amount used relative to the amount of salmon produced, are all determinants of the sustainability of the feeds, and the sustainability of the salmon production (Aas et al., 2019; Cadillo-Benalcazar et al., 2020; Pelletier et al., 2009; Ytrestøyl et al., 2015).

The use of feed ingredients changes over time as availability and price of ingredients change, and as new products are being developed. Climate changes and conflicts are examples of drivers for change in ingredient supply and development of new ingredients. An important driver is also consumer preferences with increasing interest in sustainable production with low impact on climate and use of limited resources. Production technologies used in salmon farming change over time as new technology and farming systems are being developed (Moe Føre et al., 2022). In Norway, the trend in recent years has been to keep the salmon for a longer period in land-based recirculation facilities (RAS) and transfer a larger smolt to seawater pens and semi-closed holding units. Salmon are now also transferred to seawater throughout the year except for the coldest winter months. These changes in production are driven by the problems with salmon lice that the salmon industry is

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facing, which makes frequent handling to remove the lice necessary due to resistance to chemical treatments. The genetics of the salmon itself also changes with selective breeding. These are all factors that may affect the growth and feed utilization of the salmon. Detailed knowledge of the utilization of feed resources in salmon farming thus depends on regular updating of the data.

The utilization of feed resources in salmon farming has been reported earlier (Aas et al., 2019; Ytrestøyl et al., 2015), the latest was with data for 2016. The present study is an update for 2020. The total quantities and composition of feed ingredients, origin and certification of the ingredients, and the amount of salmon produced is reported. The chemical composition of salmon is reported elsewhere (Aas et al., 2022a). A corresponding study of the utilization of feed ingredients in Norwegian farming of rainbow trout in 2020 was also performed (Aas et al., 2022b).

2. Materials and methods

2.1. Data on feed ingredients

Data on ingredients used in salmon feed in 2020 were provided by the four large Norwegian feed companies BioMar, Cargill, Mowi and Skretting, which produce close to 100 % of the feed used in Norwegian salmon farming. Information on quantity and composition of the ingredients was used for the calculations of utilization of feed and nutrients. In addition, information on origin and certification was provided. For a few ingredient batches, complete data on composition were not given. In such cases, corresponding data from other feed producers, or literature data, were used.

2.2. Chemical composition of whole body and fillet

Slaughter sized salmon were collected for chemical analysis of whole body and fillet. The data are published separately (Aas et al., 2022a). The composition of salmon varies throughout it's life cycle, and due to seasonal variations, geography and feed. The samples were collected with the intent to represent the average slaughter-sized salmon produced in Norway in 2020. Salmon of mean body weight 5.3 kg were collected in early summer and early winter, from one location in the southern part of Norway, two locations in the mid, and one location in the Northern Norway. At each sampling, ten fish were sampled for whole body analysis, and ten fish for fillet analysis. The ten fish from each sampling were analyzed as pooled samples, giving eight samples of whole body, and eight samples of fillet.

2.3. Calculations

The calculations of feed utilization reflect the utilization of feed resources in the whole salmon farming industry in Norway during one year. All losses of feed and salmon are included. The data should therefore not be compared directly to the corresponding data obtained in controlled studies or small, successful production periods. The calculations are discussed by Ytrestøyl et al. (2015) and Aas et al. (2019).

FM = fish meal, FO = fish oil.

$$\text{Economic feed conversion ratio, eFCR} = \frac{\text{Feed used (tonnes)}}{\text{Salmon produced (tonnes)}}$$

$$\text{Retention (\%)} = 100 \bullet \frac{\text{Amount of nutrient or energy incorporated in salmon (tonnes)}}{\text{Amount of nutrient or energy in the feed used (tonnes)}}$$

The retention of lipid includes lipids synthesized by the fish.

$$\text{Protein efficiency ratio, PER} = \frac{\text{Salmon produced (tonnes)}}{\text{Protein in feed (tonnes)}}$$

The lipid efficiency ratio (LER) and the energy efficiency ratio (EER) were calculated with the corresponding formulae as PER.

$$\text{Fish-in-fish-out ratio, FIFO}_{(\text{FM or FO})} = 100 \bullet \frac{\left(\frac{\text{FM or FO used in feed (tonnes)}}{\text{Yield in production of FM or FO (\%)}}\right)}{\text{Salmon produced (tonnes)}}$$

A yield of 24 % and 22.5 % was assumed for fish meal production from forage fish and cut-offs, respectively. For fish oil production, the yield varies considerably, and the average yield was estimated for the oils used in the feed. Some feed producers specified the species, in addition to origin, for each marine oil used. Yield in fish oil production for each species was identified if data were available (Cashion et al., 2017; Hilmarsdottir et al., 2020; Ytrestøyl et al., 2011). Otherwise, 5 % yield was assumed (Tacon et al., 2006). From these data, an average yield in fish oil production from the fisheries within each FAO fishing area was estimated, and this average was used when species was not given. The overall average yield was estimated to 7.6 % for the oils used in the Norwegian salmon feed in 2020.

Forage fish dependency ratio (FFDR) is calculated as FIFO, but only including FM and FO produced from forage fish.

$$\text{Marine protein dependency ratio, MPDR} = \frac{\text{FM used (tonnes)} \bullet \text{Potein in FM (\%)}}{\text{Salmon produced (tonnes)} \bullet \text{Protein in salmon (\%)}}$$

$$\text{Marine oil dependency ratio, MODR} = \frac{\text{FO used (tonnes)} + [\text{FM used (tonnes)} \bullet \text{Fat in FM (\%)}]}{\text{Salmon produced (tonnes)} \bullet \text{Fat in salmon (\%)}}$$

3. Results and discussion

This study documents the utilization of feed resources in Norwegian salmon farming in 2020. All losses such as failed productions of feed or salmon, mortality and escapees are included in the figures. The calculations do not represent biologic utilization for feed and nutrients but represent the overall utilization of the feed resources in Norwegian salmon farming. As an example, if a large volume of fish oil was lost, the retention of EPA and DHA would be reduced.

3.1. Feed ingredients

A total of 1,976,709 tonnes ('as is') of feed ingredients were used in Norwegian salmon feed in 2020, or 1,833,450 tonnes on a dry matter basis. According to public data, 1,885,000 tonnes of feed were traded. The dry matter of commercial feeds is typically around 95 %.

There were no large changes in sources of ingredients used in salmon feed in 2020 compared to 2016 (Fig. 1). There was a further reduction in the use of marine protein sources (%) and some ingredients such as insect meal and single cell proteins were included. Using single cell proteins in feed is not a new idea, neither is feeding with insect larvae. With the current demand for new ingredients and circular economy, such resources may become more important as feed ingredients in near future. These ingredients which are not within the major categories of ingredients were classified as 'other' and contributed to 0.4 % (8126 tonnes) of the feed ingredients (Fig. 1).

In 2020, soy protein concentrate was still the ingredient used in largest amount (20.9 % of the feed ingredients; Table 1) as it was in 2016 (Aas et al., 2019). Rapeseed oil represented 18.0 % of the ingredients. Marine ingredients constituted 22.4 % of the ingredients in 2020, compared to 24.9 % in 2016 (Aas et al., 2019). Due to an increase in the total amount of salmon production and feed used in 2020 compared to 2016, the amount (tonnes) of marine ingredients had increased in 2020 (Fig. 2). The use of wheat as a carbohydrate source was reduced from 8.9 % in 2016 to 6.5 % in 2020 (Table 1). Faba beans, which are a source of both carbohydrates and some protein, replaced some of the wheat. Such ingredients could be classified either as carbohydrate sources or as vegetable protein sources. Salmon have limited capacity for utilization of carbohydrates, but the relatively constant inclusion of around 10 % of carbohydrate sources is used to achieve the desired physical quality of the feed pellets.

In 1990, salmon feed was based on fish meal and fish oil, but an increasing share of the marine ingredients has been replaced using vegetable ingredients (Fig. 1). In 2020, the average Norwegian salmon feed was produced from 12.1 % marine protein sources, 10.3 % marine oils, 40.5 % vegetable protein sources, 20.1 % vegetable oils, 12.5 % carbohydrate sources, 4.1 % micro ingredients and 0.4 % of other

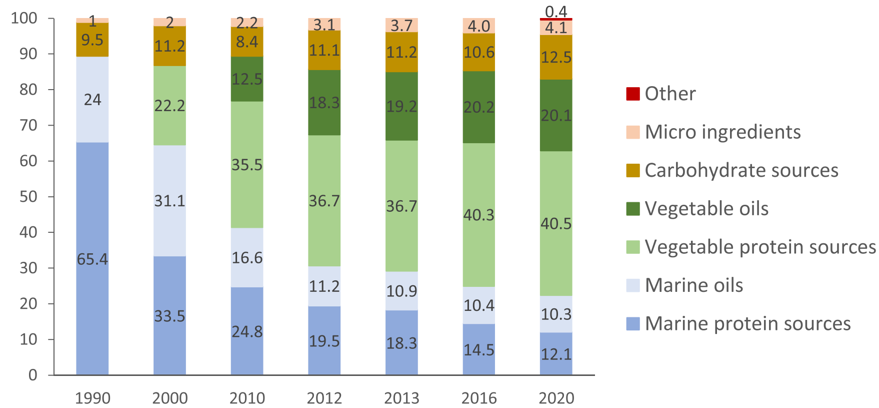

Fig. 1. Sources of feed ingredients (% of feed) in Norwegian salmon feed in 2020 compared to previous years (Aas et al., 2019; Ytrestøyl et al., 2015). Micro ingredients include vitamin- and mineral premixes, phosphorus sources, astaxanthin, crystalline amino acids. 'Other' includes insect meal, single cell protein, fermented products, and microalgae.

Table 1
Ingredients used in Norwegian salmon feed in 2020, given as tonnes and % 'as is'.

	Ingredient	Tonnes	%
Vegetable protein sources	Soy protein concentrate	413,611	20.9
	Wheat gluten	193,904	9.8
	Guar protein	84,677	4.3
	Sunflower	67,798	3.4
	Pea protein	27,306	1.4
	Corn gluten	12,971	0.7
Vegetable oils	Rapeseed oil	356,499	18.0
	Linseed oil	25,874	1.3
	Soybean oil	7392	0.4
	Camelina oil	7022	0.4
	Coconut oil	1006	0.1
Carbohydrate sources	Wheat	127,878	6.5
	Faba beans	70,568	3.6
	Pea flour	48,592	2.5
Marine protein sources	Fish meal, forage fish[a]	174,172	8.8
	Fish meal, cut-offs	65,539	3.3
Marine oils	Fish oil, forage fish	164,611	8.3
	Fish oil, cut-offs	38,986	2.0
Micro ingredients[b]	Micro ingredients	80,177	4.1
Other[c]	Other	8126	0.4
	Sum	**1,976,709**	**100**

[a] Includes 8155 tonnes of krill meal.
[b] Includes vitamin- and mineral premixes, phosphorus sources, astaxanthin, crystalline amino acids.
[c] Insect meal, single cell protein, fermented products, microalgae.

ingredients. The micro ingredients include vitamin and mineral additions, phosphorus sources, astaxanthin and crystalline amino acids. High inclusion of vegetable protein sources results in an amino acid balance different from the salmon's requirements, which is balanced with crystalline amino acids.

'Other' ingredients include insect meal, single cell proteins, fermented products, and microalgae. Some of these are produced from waste materials and have received increased attention since protein sources which can increase sustainability and contribute to a circular economy are sought for. The main challenges with novel ingredients produced from waste are the cost of the products and upscaling to production of significant amounts. In Norway, natural gas and wood biomass are substrates that are available in large quantities for production of single cell protein. Various products of single cell protein have been used for food and feed. Some of these products have been shown to be promising protein ingredients, and may even add so called 'functional' components, e.g. nucleic acids and ß-glucans, that are beneficial for fish health (Aas et al., 2006; Reveco et al., 2019; Romarheim et al., 2011; Storebakken et al., 1998; Øverland and Skrede, 2017; Øvrum Hansen et al., 2019). Despite decades with promising results in scientific trials, single cell proteins have not yet been produced in sufficient quantities and at a low enough cost to become main ingredients in salmon feed. Single cell proteins commonly contain indigestible cell wall material. For protein ingredients, the content and digestibility of protein are determinants of the products' value. Protein ingredients typically have > 60 % protein and > 80 % apparent digestibility of nitrogen. Unless the remaining content of the product has a nutritive value to the fish, ingredients with low content of digestible protein will add indigestible material, i.e., increase the amount of feces, and thus increase the waste production. Some ingredients also have low

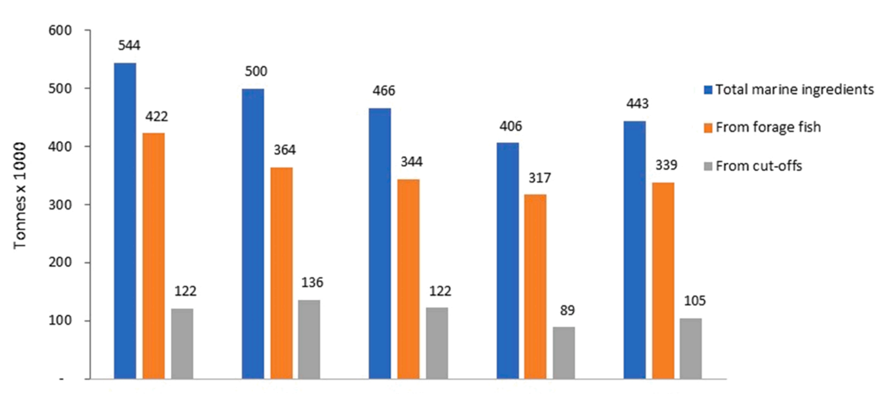

Fig. 2. Marine ingredients (tonnes × 1000) from forage fish and cut-offs used in Norwegian salmon feed in 2010–2020. Data from 2010 to 1016 are from Ytrestøyl et al. (2015) and Aas et al. (2019).

palatability. Feed intake is a main factor for fish welfare and economy in fish farming, and palatable feed is a prerequisite for successful farming. Palatability can be improved with addition of ingredients with high palatability, such as krill products.

Insect meal has been suggested as a replacement for soy in animal feeds (Cadillo-Benalcazar et al., 2020; Liland et al., 2021), and some insect meal was included in the Norwegian salmon feed in 2020. Insect larvae are a natural source of feed for salmon in the wild, and such products may have high nutritional value for the salmon (Belghit et al., 2019). However, replacing the 413,611 tonnes of soy protein concentrate of 62.2 % protein (average reported in the present data, giving 257, 266 tonnes of protein) with insect meal produced from black soldier fly larvae of 17.5 % protein (Finke, 2013), would require 1.47 million tonnes of larvae. This is strikingly similar to the amount of salmon produced. In other words, replacing today's soy protein concentrate in salmon feed with insect meal, would imply a new farmed species of the same magnitude as salmon farming itself. Insect larvae grown on waste materials is a valuable conversion of waste into protein, but to become a dominating protein source in salmon feed, a very large production is required.

Microalgae are promising sources of n-3 fatty acids and/or astaxanthin (Kousoulaki et al., 2016, 2015; Lu et al., 2021) and may in the future replace some of the marine oil, which is a limited resource. However, this will depend on development of cost-effective production of such products.

3.1.1. *Origin of ingredients*

The origin of the ingredients was given for all but 3401 tonnes (0.2 %) of the ingredients (Table 2). The origin of micro ingredients was not asked for since many of these are manufactured at laboratories and origin of the purchased product may not reflect origin of the raw materials. The FAO major fishing areas (https://www.fao.org/fishery/en/area/search) were used to identify origin of the marine ingredients. Marine protein from forage fish originated mainly from FAO fishing area 27, which includes the Norwegian coastline, and all fish meal produced from cut-offs originated from this area. Marine oils produced from cut-offs were also predominantly from FAO area 27, whereas marine oils produced from forage fish originated for a large part from the Atlantic Ocean and from the Pacific Ocean. A small amount of oil from farmed fish was used. This was from Norwegian farmed salmon and is not included in the FAO areas as farmed fish is not part of the fish stock in the area. As a globally leading producer of soy (together with the US) and thus soy protein concentrate, Brazil was the main supplier of vegetable protein sources (368,497 tonnes). A substantial amount (255,330 tonnes) of vegetable protein sources was also produced in Europe. Vegetable oils were mainly produced in Europe and Russia. The feed ingredients originating from Norway were solely fish meal and fish oil and accounted for 8.3 % of the total amount of feed ingredients used (Table 2).

The data were collected before the Russian invasion of Ukraine in 2022. Ukraine and Russia are large producers of wheat and other

Table 2
Origin of the ingredients used in Norwegian salmon farming in 2020. The FAO numbers refers to FAO's major fishing areas (https://www.fao.org/fishery/en/area/search). The contribution of ingredients produced in Norway is included in the table. The Norwegian coast is within FAO major fishing are number 27. For marine ingredients, systems for reporting origin are well developed. For vegetable ingredients on the global market, the origin of an ingredient may not be reported accurately to the buyer.

Ingredient	Sum (tonnes)	Origin	Tonnes	Norwegian (tonnes)	Norwegian (%)
Marine protein sources – forage fish	**174,172**	FAO 27	155,418	72,516	42
		FAO 34	43		
		FAO 48	8155		
		FAO 87	10,556		
Marine protein sources - cut-offs	**65,539**	FAO 27	65,539	52,166	80
Marine oil – forage fish	**164,611**	FAO 27	42,707	17,538	11
		FAO 31	45,557		
		FAO 34	22,198		
		FAO 37	2382		
		FAO 47	1916		
		FAO 51	4465		
		FAO 77	19,061		
		FAO 87	24,553		
		Undefined	1772		
Marine oil - cut-offs	**38,986**	FAO 27	30,886	22,035	57
		FAO 31	916		
		FAO 34	923		
		FAO 67	1097		
		FAO 87	633		
		Farmed fish	4531		
Vegetable protein sources	**800,266**	Europe[a]	255,330		
		Russia	38,965		
		China	47,831		
		India	84,677		
		Canada	4966		
		Brazil	368,497		
Vegetable oil	**397,793**	Europe[a]	224,068		
		Russia	173,724		
Carbohydrate sources	**247,039**	Europe[a]	247,039		
Micro ingredients[b]	**80,177**		80,177		
Other[c]	**8126**	Europe[a]	105		
		USA	2469		
		Brazil	3923		
		Undefined	1629		
Total			1,976,709	164,255	8.3

[a] Except Russia.
[b] Includes vitamin- and mineral premixes, phosphorus sources, astaxanthin, crystalline amino acids.
[c] Insect meal, single cell protein, fermented products, microalgae.

vegetable products for human consumption and for feed. Severe shortage in the global food supply, accompanied by high prices, is an immediate consequence of the war. This may force a rapid change in the use of feed ingredients in salmon feed, possibly towards increased use of e.g. single cell proteins or by change in legislations and agreements that restrict the use of certain categories of ingredients. There are several sources of protein and lipids that are presently not used in large scale in salmon feed (Albrektsen et al., 2022; Almås et al., 2020; Eidem and Melås, 2021). Global shortage and high prices of ingredients are strong incentives to solve the challenges limiting the use of alternative ingredients.

The recent pandemic, conflicts and uncertainty on global effects of climate changes have increased the attention to self-sufficiency of food products in many countries. Norway produced 273 kg salmon per capita in 2020, but the production depended on import of 91.7 % of the feed ingredients. Norway exported 1,141,072 tonnes of salmon (Statistics Norway, 2022), which corresponds to 78 % of the total amount produced. Norway does not have climate and growth conditions that allow production of protein rich plants for self-sufficiency of feed ingredients for today's animal production. Single cell proteins produced from natural gas and wood biomass are ingredients that theoretically have potential to be produced in a very large scale in Norway. So far, the cost is a limitation for their use as feed ingredients for salmon, but the rising prices on food and feed commodities may lead to the upscaling of such products and bringing the productions costs down.

3.1.2. Environmental certification of ingredients

For marine ingredients, several certification systems for fisheries or producers/products are developed. In addition, there are systems for Fishery Development Projects (FIPs) aiming to move fisheries or producers towards sustainability. The amount (%) of marine ingredients originating from certified fisheries is shown in Table 3. Some ingredients are certified by more than one system, and the per cent reported under all systems cannot be summed. But the data show that most of the marine ingredients used in salmon feed are from fisheries approved by at least one environmental certification standard (Table 3).

For vegetable ingredients on the global market, certification systems are not as well established as for the marine ingredients. The relevant environmental certifications for the vegetable products are mainly concerning deforestation. All soy protein concentrate used in the Norwegian salmon feed in 2020 was certified as deforestation-free (Table 3).

Table 3
Amount (%) of ingredients in Norwegian salmon feed in 2020 that originated from fisheries or companies certified by different certification standards. One ingredient can be approved by several standards and the amount certified by different standards can therefore not be summed.

	Marine trust[a]	MSC[b]	Marine trust FIP[c]	MSC FIP[d]	Certified deforestation-free[e]
Fish meal from forage fish[f]	68	80	13		
Fish oil from forage fish	63	45	32	5	
Fish meal from cut-offs	86	86	7		
Fish oil from cut-offs	69	61	3		
Soy protein concentrate					100

[a] https://www.marin-trust.com/.
[b] https://www.msc.org/.
[c] https://www.marin-trust.com/programme/improver-programme/accepted-fips.
[d] https://www.msc.org/for-business/fisheries/developing-world-and-small-scale-fisheries/fips.
[e] https://www.proterrafoundation.org/, http://www.donausoja.org/.
[f] Includes 8155 tonnes of krill meal.

3.1.3. Non-GM certification of ingredients

According to Norwegian legislation, ingredients with genetically modified organisms are not allowed in feed unless especially applied for and approved by the authorities. All of the soy protein concentrate used was reported as certified non-GM (non-genetically modified) by the Proterra and Europe Soy/Donau Soja standards (https://www.proterrafoundation.org/, http://www.donausoja.org/). According to the feed producers, all ingredients used were non-GM although not all ingredients had such certification.

3.1.4. Chemical composition of the feed

The average Norwegian salmon feed in 2020 contained 92.8 % dry matter, 37.0 % crude protein, 29.6 % crude lipid, of which 2.2 % EPA + DHA (eicosapentaenoic acid, 20:5n-3 and docosahexaenoic acid, 22:6n-3) and 3.7 % n-6 fatty acids, 4.3 % carbohydrates, 15.3 % NFE, 2.1 % crude fiber and 0.94 % phosphorus. The energy content was 24.7 MJ/kg (Table 4). Compared to 2016, the lipid content was lower, the EPA + DHA content was slightly lower, the content of n-6 fatty acids was increased and the phosphorus content was reduced (Aas et al., 2019). The reduction in phosphorus concentration may be due to an increased use of the highly digestible phosphorus sources.

A complete carbohydrate analysis is probably not performed for all vegetable protein ingredients. These ingredients may contain a variety of carbohydrates, in which a certain part is indigestible. Carbohydrates, NFE (nitrogen free extract) and crude fiber all include carbohydrates. The data in Table 4 are given as provided by the feed producers. The carbohydrates is the fraction of the ingredients with the largest uncertainty in the data.

3.2. Amount of salmon production

The total quantity of salmon produced in Norway in 2020 was estimated to 1,467,655 tonnes. This figure was calculated from the registered traded amount of 1,377,185 tonnes (Directory Of Fisheries, 2021) corrected for an increase in biomass during the year from 812,410 tonnes 31. December 2019 to 902,879 tonnes 31. December 2020. The amount of salmon traded in 2020 was the highest amount traded during one year in Norway (Fig. 3).

Assuming a fillet yield of 65 %, 953,976 tonnes of fillet was produced. This figure represents 'edible part' in the calculations.

3.3. Composition of whole body and fillet of slaughter sized salmon

Whole body and fillet were analyzed for energy, dry matter, ash, selected minerals, nitrogen, individual amino acids, total lipids and individual fatty acids. The chemical composition of whole body and fillet is published separately (Aas et al., 2022a).

In the present study, salmon for both whole body analysis and analysis of edible part was collected and analyzed. In 2016, only salmon for whole body analysis was collected especially for the purpose, and the edible part was represented by public data on fillet composition. Whole body and fillet were both intended to represent the Norwegian salmon, but different sampling regimes was a weakness in those data from 2016 (Aas et al., 2019). In the present study, salmon for analysis of whole body and edible part are collected from the same productions.

The samples of whole body and edible part were collected with the intention to represent variations in geography, time of the year and feed producer, but these fish represent nearly 1.5 million tons of salmon with variations in composition. Calculations using data on body composition should therefore be considered as approximate values and small differences should not be given too much attention. Besides, feed data is collected for one year, whereas the salmon is produced over more than one year. The calculations including body composition are only valid if

Table 4
Estimated average composition, the total amount of nutrients used, the amount of nutrients from marine, vegetable, micro and other ingredients in Norwegian salmon feed in 2020. Minerals other than phosphorus are not given, nor is ash and micro ingredients. Energy data are given as MJ/kg or GJ.

	Average composition of Norwegian salmon feed in 2020 (% or MJ/kg)	Total amount of nutrients used in Norwegian salmon feed in 2020 (tonnes or GJ)	Nutrients from marine ingredients (tonnes or GJ)	Nutrients from plant ingredients (tonnes or GJ)	Nutrients from micro ingredients (tonnes or GJ)[a]	Nutrients from other ingredients (tonnes or GJ)[b]
Dry matter	92.8	1,833,450	407,099	1,358,567	59,821	7963
Energy	24.7	48,784	12,554	35,507	443	280
Crude protein	37.0	732,127	164,687	554,718	12,292	431
Crude lipid	29.6	585,990	226,093	353,533	10	6353
EPA + DHA	2.2	44,393	41,183	0	0	3210
n-6 fatty acids	3.7	72,546	5117	67,371	0	58
Carbohydrates[c]	4.3	85,223	14	85,208	0	0
NFE[c]	15.3	302,231	86	299,521	1689	934
Crude fiber[c]	2.1	41,831	160	41,629	0	42
Phosphorus	0.94	18,653	5460	6985	6207	1.0

[a] Includes vitamin- and mineral premixes, phosphorus sources, astaxanthin, crystalline amino acids.
[b] Insect meal, single cell protein, fermented products, microalgae.
[c] It varied among feed producers and among ingredients if data for carbohydrates, NFE (nitrogen free extract) or crude fiber were given. The table shows the data as provided from the feed producers.

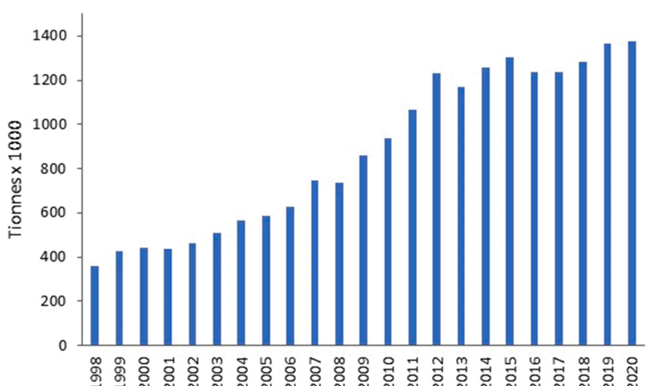

Fig. 3. Annual amount (tonnes × 1000) of traded salmon in Norway in 1998–2020 (Directory Of Fisheries, 2021).

the utilization of feed resources is relatively stable during the salmon's life cycle.

3.4. Efficiency of utilization of feed ingredients

The ratio amount of salmon produced versus the amount of feed ingredients or nutrients used represents the efficiency of utilization of feed resources. Various calculations and indices are used to express this utilization efficiency. Some of the formulae used are the same as used in nutritional studies. In the present study however, the utilization efficiency is calculated for the whole salmon farming industry in Norway during one year, i.e., the total 'cost' of having a salmon farming industry is accounted for. All losses of feed ingredients, feed and fish are included in the calculations and the data on feed utilization estimated are a mass balance of nutrients in a whole production system. This contrasts with nutritional studies, where the utilization of the feed eaten is calculated and the fish' biologic ability to utilize the feed and nutrients is studied. Consequently, calculations and indices from the present study are not directly comparable to data obtained in controlled studies where the efficiency will be higher.

3.4.1. Economic feed conversion ratio (eFCR)

The eFCR for Norwegian salmon production in 2020 was 1.35, 1.25 or 1.28 depending on if data on feed ingredients 'as is, feed ingredients on dry matter basis or traded feed, respectively, were used to express the feed used in the calculation. This is slightly higher than in 2016 (1.30, 1.21 or 1.23, respectively; Aas et al., 2019). The eFCR is the weight: weight ratio of feed used, and fish produced. An increase in the eFCR may have numerous causes related to feed ingredients, feed, feed intake, feed utilization, temperature, delousing procedures, outbreak of decease, size at slaughtering, body composition, and biomass of mortalities and escapees. The incidents of escapees were low in 2020 (Directory Of Fisheries, 2022) and did not contribute to increased eFCR compared to 2016. In 2020, the COVID-19 pandemic affected import and export of all goods worldwide, and this may also have affected slaughter size and timing of slaughtering of salmon or feeding strategies prior to slaughtering. Some salmon feed is used for trout farming, and there may also be an inaccuracy at new year of what is registered on the last or the new year for feed ingredients, feed and biomass of salmon. However, data collected on this overall level do not have the accuracy of data from controlled studies, and minor changes in eFCR may be of moderate importance. Trends and changes over time are important for the understanding of the utilization of resources.

3.4.2. Retention

The retention calculated in the present study, estimates how much of a nutrient or energy from the total amount of feed ingredients, is retained in the fish produced during one year in Norway. In the corresponding study with data for 2016 (Aas et al., 2019) we suggested using the term 'resource economic retention'. Although the calculation is the same as in nutritional studies, the data for retention estimated in the present study are collected differently and represent an overall flow of the nutrients and energy from feed ingredients in the salmon farming industry. In contrast, retention data in nutritional studies express the salmon's retention of nutrients and energy from the ingested feeds used in that study.

As for the eFCR calculations, all losses of feed and fish are included. The retention of dry matter, energy, crude lipid, the n-3 fatty acids EPA+DHA, protein and phosphorus was calculated for whole body of the salmon, fillet and cut-offs, and the amount not retained was considered as loss (Table 5). Compared to the data from 2016 (Aas et al., 2019), the retention of total lipid and of EPA + DHA in whole body and fillet was increased (Fig. 4.). In the present study, the edible part was analyzed as a whole fillet with skin on. In previous studies, public data on fillet were used. These are based on the NQC (Norwegian quality cut) which is known to have lower lipid and n-3 concentration than the complete fillet. Also leaving the skin on contributes to increase the lipid and n-3 concentration. The sampled salmon from one location were fed a feed especially high in n-3 fatty acids prior to slaughtering, and this may have contributed to a higher n-3 concentration in the fish than if fed with a standard feed. The retention of phosphorus was also higher in 2020 than in 2016 (Aas et al., 2019). There has been a change to more

Table 5
Retention (%) of nutrients and energy in whole body, fillet and cut-offs of salmon, and nutrients and energy not retained (loss) in Norwegian salmon produced in 2020.

	Retention in whole body	Retention in fillet[a]	Retention in cut-offs[b]	Not retained – loss[c]
Dry matter	33	21	12	67
Energy	39	25	14	61
Crude lipid[d]	57	35	23	43
EPA + DHA	49	32	17	51
Protein	34	25	9	66
Phosphorus	25	12	12	75

[a] 65 % fillet yield was assumed.
[b] Retention in whole body (%) – retention in edible part (%).
[c] 100 (%) – retention in whole body (%).
[d] Includes lipids produced from non-lipid precursors.

digestible phosphorus additions in the recent years, which may have affected concentration of phosphorus in feed and the retention of phosphorus.

Apart from the sources of errors and inaccuracy in this study as discussed above, the retention data for the edible part will depend on fillet yield and what is considered as edible part. In the calculations, 65 % fillet yield for salmon was used. The same figure was used in previous studies (Aas et al., 2019; Ytrestøyl et al., 2015) which allows direct comparison among data from the different years. What is edible part of the salmon is debatable and differs among different cultures. The retention in cut-offs is calculated by difference (retention in whole body – retention in fillet) and will depend on the retention data for fillet. It should be noted that all cut-offs from salmon processed in Norway are recycled for human consumption (n-3 supplements) or animal feed (Richardsen et al., 2017). The only exception is blood, which accounts for approximately 3 %, and even for blood, further use is under development. For whole salmon exported to other countries we have no data on use of cut-offs, or how much of the fish is considered edible.

3.4.3. Protein-, lipid- and energy efficiency ratios, (PER, LER and EER)

PER is a measure of the weight gain per unit of protein fed. LER and EER are the corresponding measures for lipid and energy, respectively.

PER, LER and EER are measures of how much of protein, lipid and energy from the feed ingredients is retained in the produced fish. As for other measurements of utilization of the feed resources described above, the calculations are the same as in nutritional studies, whereas the data in the present study are collected on an overall scale and express the

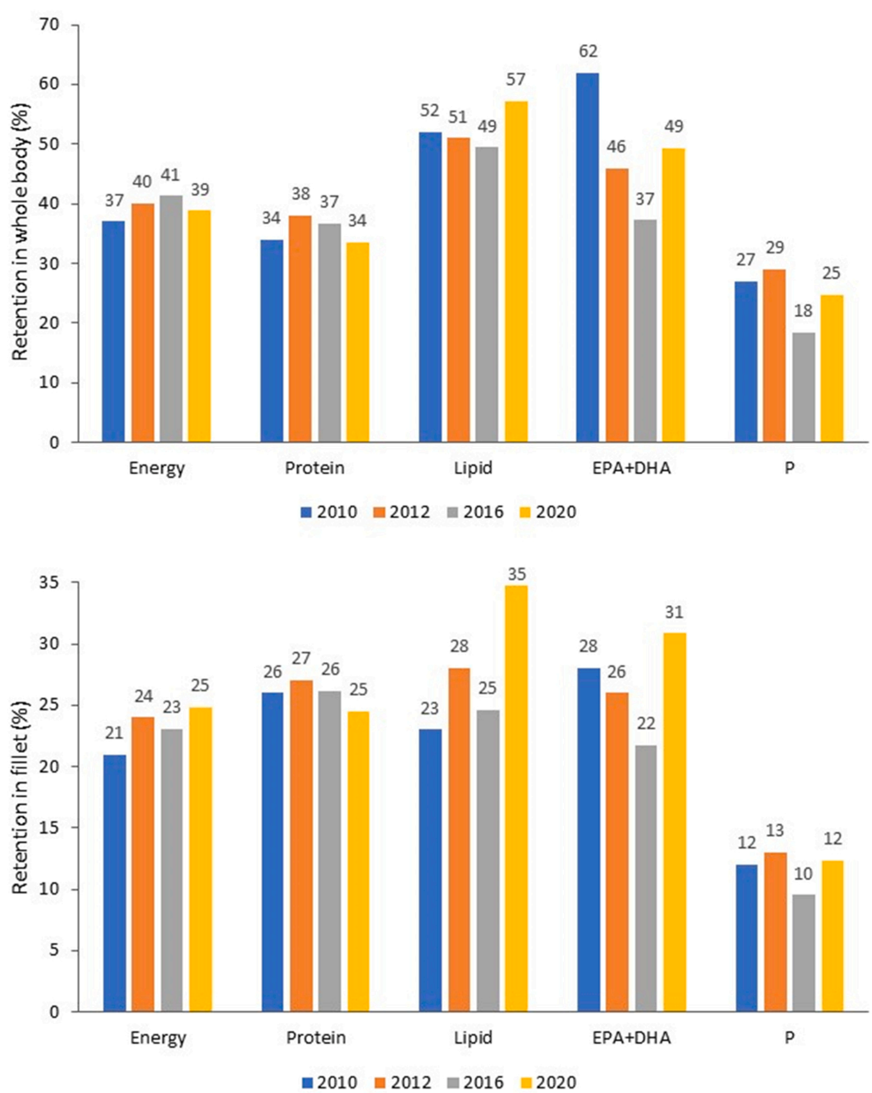

Fig. 4. Retention of nutrients and energy in whole body (upper panel) and fillet (lower panel) of salmon produced in Norway in 2010, 2012 (Ytrestøyl et al., 2015), 2016 (Aas et al., 2019) and 2020.

utilization of feed resources in the whole Norwegian salmon farming industry during one year (Fig. 5).

3.5. Indices for use of marine ingredients

There are some commonly used indices that calculate the use of marine ingredients in salmon feed. In some contexts, marine ingredients have been considered as less sustainable than vegetable ingredients. However, sustainability is a complex matter including resource management, emissions, deforestation, use of freshwater, phosphorus, energy and land area, and even social aspects and economy. Whether an ingredient is of marine, or vegetable origin does not give any information about the ingredient's sustainability. The indices for use of marine ingredients are also discussed by Ytrestøyl et al. (2015) and Aas et al. (2019).

3.5.1. Fish-in-fish-out ratio (FIFO)

The FIFO is meant to be a simple measure of how much fish is used to produce new fish and is a weight:weight ratio of marine ingredients used for the feed versus the salmon produced. The yield is different for production of fish meal and fish oil, and the amount of fish meal and fish oil in the feed is different. The FFIO is therefore calculated for fish meal and fish oil separately. The FIFO does not differentiate between cut-offs or forage fish. The estimated FIFO for fish meal in 2020 was 0.7, which is a small change from 0.8 in 2016. The FIFO for fish oil was 1.8 in 2020 compared to 1.5 in 2016 (Fig. 6; Aas et al., 2019).

The yield in production of fish meal is relatively constant, typically ranging from 22 % to 25 %. The yield in fish oil production is far more variable, as fat content varies considerably between species, but also within species depending on harvesting time, and from year to year. For instance Atlantic herring (*Clupea harengus*) which is an important species for fish oil production for Norwegian salmon feed, varies in fat content from below 5 % to above 16 % (Kenyon et al., 2021). It is often assumed a yield of 22.5 % for production of fish meal, and 5 % for fish oil (Tacon et al., 2006) in FIFO calculations. Norwegian salmon feed contains fish oil from species which differs considerably from 5 % yield and was estimated to 7.6 % on average. Even with a high degree of detailed information on the fish oils used, only approximations for the average yield of fish oil production could be estimated for feed representing the whole Norwegian salmon production. The value for yield (%) in fish oil production used in FIFO calculations has a certain level of error, and there is a corresponding uncertainty in FIFO estimates for fish oil. The commonly used 5 % yield in fish oil production, gives FIFO 2.8 for fish oil, whereas using 9.3 % yield, as estimated in previous studies (Aas et al., 2019), results in FIFO 1.5 for fish oil. Given the uncertainty in the yield in fish oil production, the FIFO for fish oil in a large production such as the present, can only be calculated as a very rough estimate. The minor changes in FIFO and FFDR of fish oil found from 2012 to 2020 (Fig. 6) are all within a range that can be explained by moderate inaccuracy of the yield (%) in fish oil production used in the calculations.

FIFO has been used as a criticism of using fish to produce fish instead of using the wild fish resources for human consumption, and that

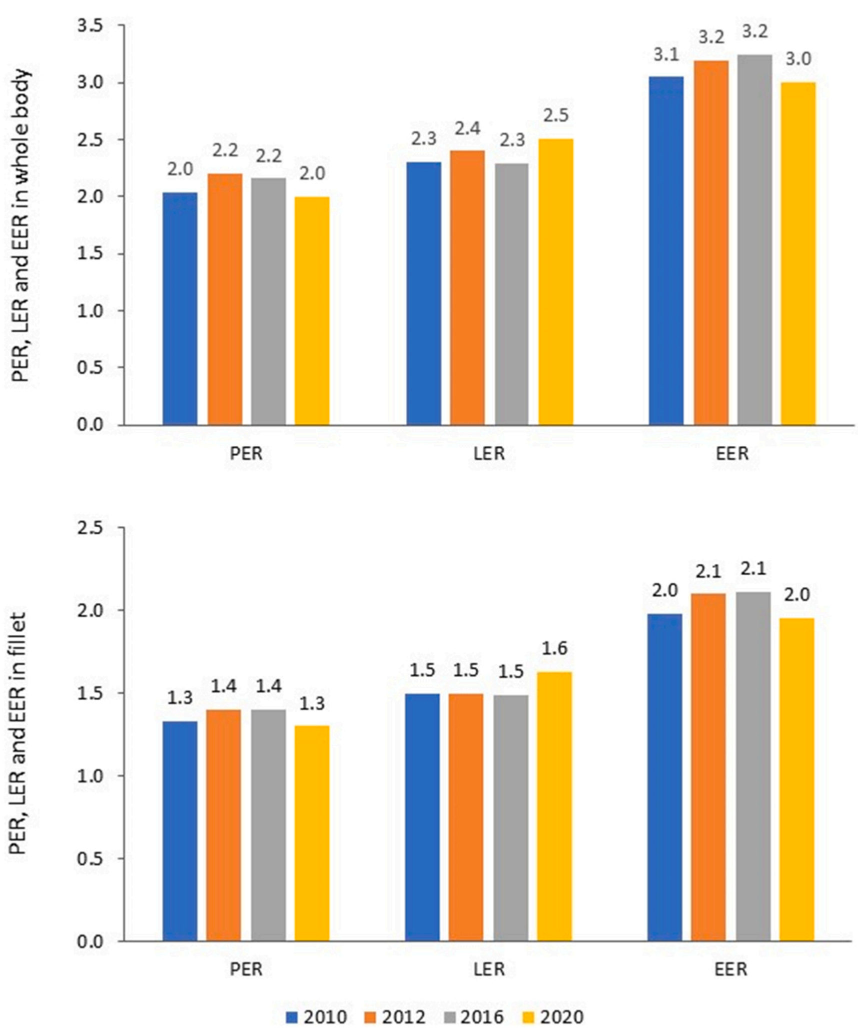

Fig. 5. Protein efficiency ratio (PER), lipid efficiency ratio (LER) and energy efficiency ratio (EER) in whole body and fillet of salmon produced in Norway in 2020.

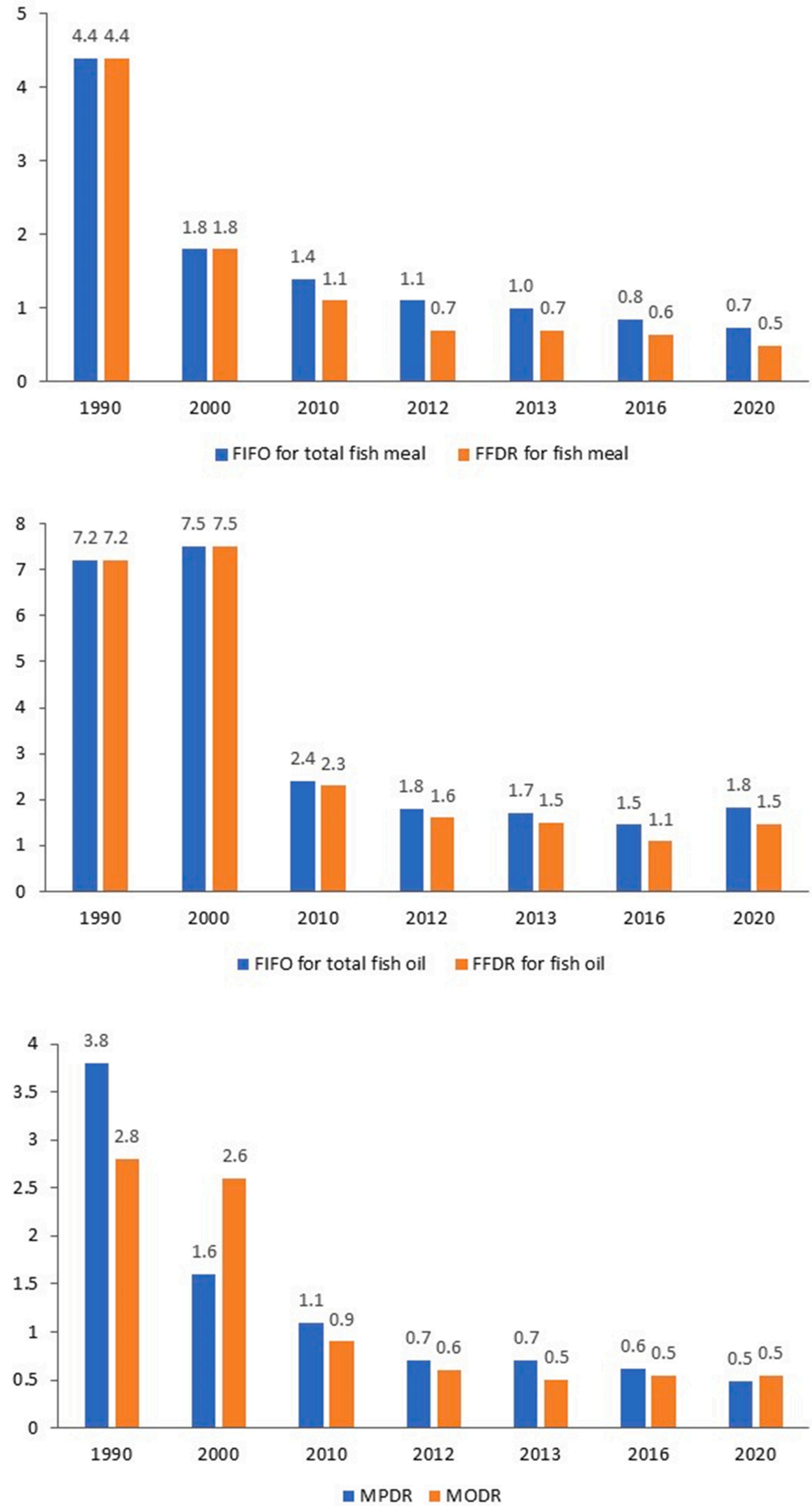

Fig. 6. Fish-In-Fish-Out-ratio (FIFO) forage fish dependency ratio (FFDR) of fish meal (upper panel) and fish oil (middle panel), and marine protein dependency ratio (MPDR) and marine oil dependency ratio (MODR) from forage fish (lower panel) in Norwegian salmon farming in 1990, 2000, 2010, 2012, 2013 (Ytrestøyl et al., 2015), 2016 (Aas et al., 2019) and 2020.

aquaculture feeds containing forage fish is not a sustainable solution. However, marine ingredients sourced from certified fisheries, or produced from cut-offs, may be among the more sustainable feed ingredients. They are renewable and do not consume fertilizer, freshwater resources or occupy valuable farmland. Corresponding ratios could also be calculated for the use of vegetable ingredients, terrestrial ingredients, or soy, wheat, corn and so forth. However, some of the vegetable protein sources in feed are biproducts from sugar production. Maybe the use of wheat and corn for candy production should be questioned rather than the use of biproducts as protein sources in feed. In fact, if using aquaculture sludge as a fertilizer in agricultural fields, an index for amount of fish used in e.g. wheat production could also be calculated. In other words, indexes for the origin of all input factors in a production system can be calculated, but do not necessarily give any relevant information about sustainability. The FIFO is not an indicator of sustainability, it merely shows the amount of ingredients originating from the marine environment. This, together with the high level of uncertainty in the calculation of FIFO for fish oil, raises the question of what the purpose of estimating the FIFO is, what it should be used for, or whether it should be used at all.

3.5.2. Forage fish dependency ratio (FFDR)

The FFDR is calculated as the FIFO, except that only fish meal and fish oil from forage fish are included. The FFDR is thus a weight:weight ratio of forage fish used for the feed versus the salmon produced. The estimated FFDR for fish meal and fish oil in 2020 was 0.5 and 1.5, respectively (Fig. 6). In 2016, the corresponding figures were 0.6 and 1.1, respectively (Aas et al., 2019). The uncertainty in the estimated FFDR related to the yield (%) in fish oil production is as discussed for FIFO.

3.5.3. Marine nutrient dependency

The marine nutrient dependency ratios (Crampton et al., 2010) express the dependency of marine resources in the salmon production. The marine protein dependency ratio (MPDR) and marine oil dependency ratio (MODR) in 2020 were both 0.5 (Fig. 6), which is very similar to 2016 (Aas et al., 2019). Only fish meal and fish oil from forage fish were included in the calculations. As for FIFO and FFDR, the marine nutrient dependency ratios are not a measure of sustainability. Similar ratios could have been calculated for vegetable ingredients.

4. Concluding remarks

In the present project, the data on the feed utilization in production of Atlantic salmon and rainbow trout in Norway in 2020 were documented. The data on rainbow trout are published separately (Aas et al., 2022b). Some trout farmers in Norway use salmon feed for the trout, and the amount of this could not be quantified. This results in an underestimation of the efficiency of utilization of feed resources in salmon and overestimates the efficiency in trout production. The most correct data are therefore obtained when given as a sum for the two species. The production of rainbow trout is however only 6 % of that of the salmon production, and data on salmon are to a very small degree affected by data on rainbow trout. Data on the two species together are presented in Aas et al. (2022b).

The data showed that there were minor changes in the utilization of feed resources in 2020 compared to 2016 (Aas et al., 2019), except for an increase in the amount produced and a small increase in eFCR. Some ingredients such as single cell protein and insect meal were included in 2020. These constituted 0.4 % of the ingredients. There is a large ongoing effort to develop such ingredients. The coming years will show whether these ingredients can be produced in sufficient quantities and at a low enough cost to be used in significant amounts in feed.

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CRediT authorship contribution statement

Turid Synnøve Aas: Data curation, Project administration, Writing – original draft. **Torbjørn Åsgård:** Data curation, Validation, Writing – review & editing. **Trine Ytrestøyl:** Methodology, Writing – review & editing.

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.

Data Availability

The data that has been used is confidential.

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