Microalgae for Salmon Feed

Supply Chains, Markets and Sustainability

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Summary

The report is elaborated as a Deliverable in the project "Development of filtration technology for microalgae for sustainable fish feed – FIMAFY". The project has received funding from GUDP.

An increasing global demand for salmon is a strong driver for a growing demand for fish meal and fish oil, and the need to find alternative feed sources remains evident. Microalgae holds an interesting potential for filling this gap as microalgae can be cultivated and processed into omega-3 fatty acids like EPA and DHA which are essential nutrients normally provided with the fish oil. The global salmon industry is centered on salmon farming companies and fish feed manufacturers. Norway and Chile are the largest salmon producers in the World. Feed is supplied by few but global feed companies. A common pattern across the salmon feed industry is an emerging use of microalgae-derived EPA and DHA in salmon feed; a pattern which is emerging through joint-ventures and collaboration agreements with large-scale microalgae processors.

As salmon farming is rooted in intensive production systems and feed is the largest group of costs, the requirements for compound feed with a high feed conversion rate and sufficient supplies of nutrients are obvious. For microalgae-derived feed ingredients to enter into this supply chain, the quantities and qualities of the ingredient has to meet the specifications, technology and trading practices applied by the feed manufacturers. The industry is global and the supply chains for feed ingredients, feed and salmon span across continents.

The global salmon feed industry is cost-and-volume driven, meaning that suppliers of microalgae-derived ingredients such as omega-3 fatty acids must operate in an industrial scale to allow for supplies in sufficient quantities. As the global market for fish oil for use in salmon feed is estimated at 580,000 tons it is evident that the market for omega-3 fatty acids (EPA and DHA) also has to be calculated in hundred thousands of tons.

Microalgae can be cultivated and processed in a variety of ways such as open pond or tank cultivation. Products derived from processing of microalgae and targeted the fish feed industry include whole algal meal, algae paste and special ingredients such as omega-3 fatty acids. Companies that produce EPA and DHA from microalgae are located in the USA, Brazil and Europe. As the global production of microalgae-derived ingredients for salmon feed expands, the supply chains for EPA and DHA will become more resilient. This will encourage the inclusion of microalgae-derived omega-3 fatty acids in salmon feed. Improved strains, cultivation methods and, processing of microalgae-derived ingredients are essential steps to conquer for the application of microalgae into salmon feed to become the "new normal". Sustainability is a key driver for this development pattern. Consumers may have sustainability criterions for purchasing salmon, and some certification schemes exist that promote sustainable fish farming.

Performance of novel feed sources has to match the performance of fish meal and fish oil in terms of functionality, nutrition and economics; thus a triple-bottom line. But, when industrial-scale microalgae-ventures are being established and the supply chain for EPA/DHA in salmon feed is functioning there seems to be no doubts about the future perspectives for microalgae derived ingredients: They are game-changers and will play a strong role for a continued transition towards a more sustainable salmon farming industry.

Contents

Chapter 1 Introduction

1.1 Introducing the report

This report provides a qualitative analysis of the supply chain for microalgae-derived ingredients for salmon feed with the overall aim of mapping the supply chain and understanding its dynamics. Let this statement be a starting point of the report:

"Global aquaculture output will double in size from 35 million tons in 2005 to 70 million tons in 2035, and the 70 million tons of fish and seafood would require 95 million tons of feed, and there is a supply gap for omega-3 fatty acids"[1]. This is the challenge the FIMAFY project has been working to find solutions to with special reference to microalgae as renewable sources for production of omega-3 fatty acids (EPA and DHA), and high quality proteins which can replace fish meal.

The report provides information about how the supply chain for microalgae in salmon feed is structured; explains the dynamics taking place in relation to this chain; and draws conclusions about the market potential for using microalgae in salmon feed production. The report will only address feed for salmon.

A wide range of microalgae species are produced for commercial use (for bioenergy, high value compounds and feed) around the world. In relation to salmon feed, the potential for microalgae is related to the species' ability to substitute DHA and EPA; also known as omega-3 fatty acids, which are essential nutrients for salmons and, supplied from fish meal and fish oil today. EPA and DHA are also referred to as LC PUFAs (long-chain poly-unsaturated fatty acids). Microalgae may also have a potential to at least partially substitute fish meal. The report is elaborated with a focus on *Chlorella Sp* and *Nannochloropsis Sp* as these species contain high levels of PUFAs. Some *Chlorella Sp* is also rich in proteins. Microalgae are also used for various live feed e.g. rotifers and artemia etc. which the fish larvae feed on. The report does not analyze this sub-segment of the supply chain for microalgae for fish feed.

The report will provide an overview of the supply chain structure and major players in the microalgae business, the salmon feed industry, and the markets for salmon. Also the most important drivers and barriers for using microalgae-derived ingredients in salmon feed and for developing the supply chain for microalgae targeted at salmon feed production are investigated. As the salmon feed industry is global and microalgae for fish feed are traded across continents, this report is elaborated with a global perspective.

The report is elaborated as a Deliverable in the FIMAFY project. It provides information that feeds into the detailed business plans that will be elaborated for the industrial partners of the project hence, microalgae as an ingredient in salmon feed and, technologies for downstream processing of microalgae.

1.2 Methodology

The report is elaborated as a qualitative analysis aiming to describe and understand the supply chain and most important mechanisms with an impact on the supply chain. This is understood as the "supply chain dynamics".

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[1] Aurora Algae, 2015

Elaboration of the report is based on desk-research and consultations with stakeholders and project partners. Desk research has been carried out over a period of two years to properly understand the dynamics of the supply chain, thus the report provides in a retrospective view, a presentation of the present situation. Especially the understanding of trends in the microalgae industry and the coherence between market demand and market mechanisms has benefitted from this long research period. During the project, several draft versions of the report has been presented at project meetings to clarify issues related to microalgae production, feed formulation and feed quality parameters, and about PUFAs. Input from project partners have contributed to refining the supply chain analysis to the state presented here.

In addition to project partners' input, IFAU has also consulted with stakeholders at Danish and European conferences and workshops to obtain insights to the principles of supply chain dynamics, green innovation and green technologies, and the microalgae business.

Desk research has included reviewing academic literature, business reports, trade magazines, newsletters, international statistics and company reports. Topics that have been studied through literature include among other topics: microalgae production, species, microalgae and EPA/DHA, prices, market trends, technologies and systems for microalgae production, the salmon feed industry, recipes, the market for salmon feed, the market for salmon, and consumer market trends. In the report, all references are mentioned in footnotes and a full list is provided in the section References.

Gathering prices for microalgae and microalgae-derived ingredients has proven nearly impossible due to confidentiality issues of the algae producers. Following this, the report only presents prices that have been derived from literature making comparisons across the microalgae products and with currently used feed sources complicated and with great uncertainties. It has been decided to elaborate this report with a qualitative approach to illustrate the coherences and markets in the supply chain and provide examples of businesses and prices; it is not an economic analysis of the competitiveness of microalgae in the context of feed for salmon. For some aspects in the report it has been necessary to provide estimated values. Here the best base values for providing an estimate is presented and the base values may be updated once improved figures would be available. Information about estimated values is given in footnotes.

The views presented in the report are the author's.

1.3 About the report

In chapter 2, the global salmon industry is presented and the main market trends for salmon. This sets the scene for formulating salmon feed and investigating the ingredients used in feed formulation in chapter 3. Chapter 4 explores the microalgae industry and major producers, and chapter 5 discusses supply chains and sustainability aspects, and conclusions are drawn up.

Chapter 2 Presenting the global salmon industry

2.1 Global salmon production and markets

Salmon farming started as in industry in Norway in the 1980's and in Chile in the 1990's. Today, salmon are also farmed in the Faroe Islands, Iceland, Australia and New Zealand[2].

By 2017, the global salmon production was calculated at 2,248,000 tons and this constituted approx. 3 % of the global aquaculture production and wild catches across species[3]. The main farmed species is Atlantic salmon accounting for 93 % of the production, and Pacific salmon for the remaining share. Pacific salmon is produced in Chile whereas the Atlantic salmon is farmed in Canada, Norway and the EU (particularly the UK)[4]. Norway is the largest producer of salmon with a harvest of 1.27 million tons in 2017 and forecasted harvest for 2018 of 8 % more. Chile is the second largest salmon producer with a forecasted harvest of 823,000 tons in 2018; this is 7-8 % more than the previous year. The remaining 11 % of the global salmon production is shared between the United Kingdom and Canada[5]. The EU production of salmon is approx. 180,000 tons of which the UK produced nearly 166,000 tons followed by Ireland (approx. 12,000 tons) and Poland (2,000 tons)[6], figure 1.

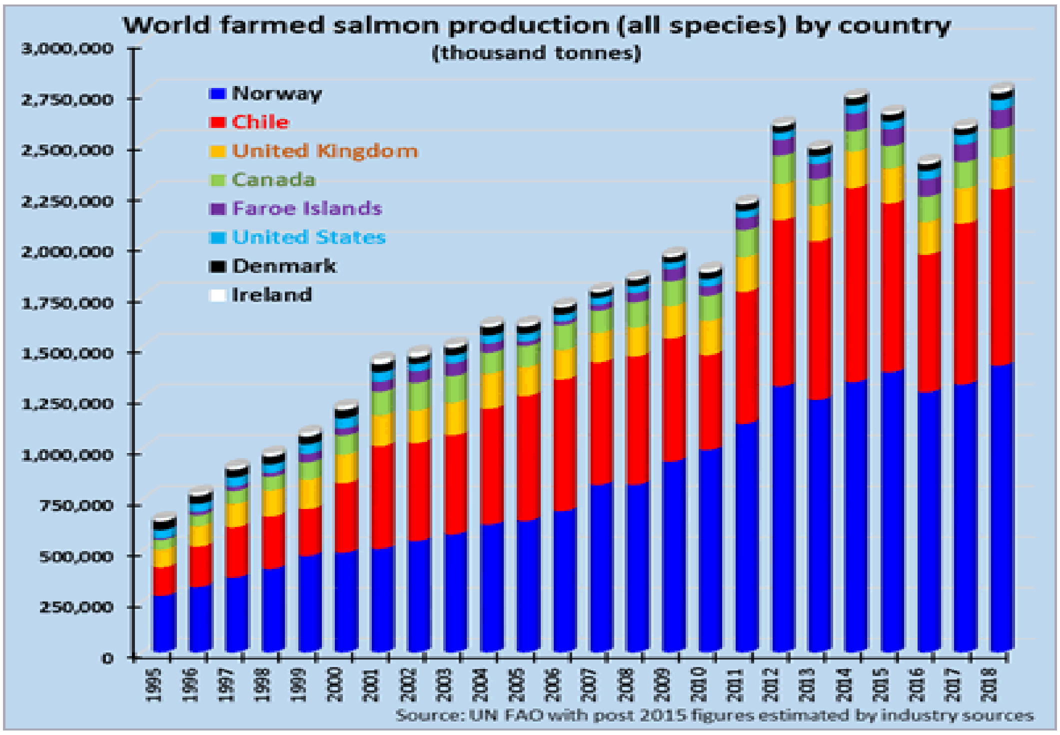

Figure 1: Development in global salmon production

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2 www.globalsalmoninitiative.org
3 BioMar Sustainability Report with data from FAO
4 European Commission, 2012
5 FAO Globefish market report Sept. 2017
6 Nielsen and Motova, 2014

Salmon is a product with a global market, in which the core markets are the EU-28, USA and Japan. The core markets show only modest growth. The largest import markets for salmon are France, Germany, USA, Japan, Russia and China. The French market has been affected by increased prices on salmon in 2016 due to reduced harvests in Norway and Chile, and this high prices have not yet settled down to regular levels, thus consumer demand is lagging behind. A similar trend is witnessed in the German market where imports in 2017 have not climbed to the volumes prior to 2016. With a positive economic outlook the German market is forecasted to grow slightly in 2018. The US market imported 272,000 tons of salmon during the first three quarters of 2017; nearly 3 % more than the previous year. Chile and Norway are the main suppliers to the American market at the expense of Canada[7]. In Asia, particularly the Chinese market shows strong growth rates for imports of salmon; a growth fueled by an increasing demand from urban affluent consumers in major cities. It is also worth noting that China imports Norwegian salmon to be filleted and frozen for re-exporting[8]. In China and Japan there is a growing demand for salmon and, at the same time an increasing consumer demand for organic food products. Research about consumer trends in China and Japan reveals that a main driver for buying organic products including seafood is sustainability and in this context a resource-efficient and renewable feed source such as microalgae could well become associated with sustainably produced salmon[9].

2.2 Prices and salmon markets

2.2.1 Global salmon prices

Prices on salmon are in general related to global supply and demand. This means that when incidents with a major impact on salmon production prices tend to reflect this. An example is the algal bloom in Chile in 2016 that resulted in severe decline in the salmon production. Chile is still recovering from this incident. In Norway, the salmon production was also tight in 2016 and this resulted in high export prices which several export markets are still marked by. In 2017 and for 2018, Norwegian salmon production has increased but the prices have not yet fully returned to the level of 2016, figure 2.

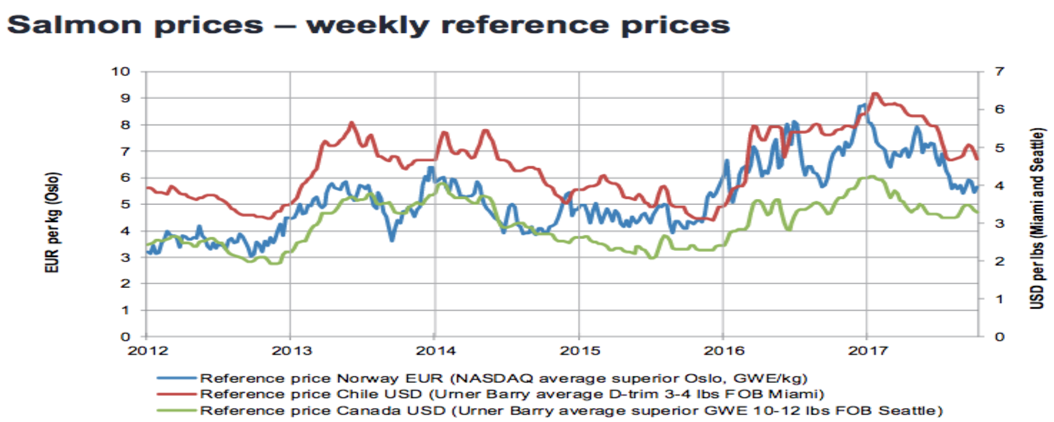

Figure 2: Prices for salmon in Norway, Chile and Canada

[7] FAO Globefish market report Sept. 2017
[8] European Commission, 2012
[9] Hamann, 2018

The high price of fish meal which is being driven by both falling supply and rising demand will polarize the global aquaculture industry whereby production will favor species that require lower priced feed with low inclusion rates of marine ingredients or those that receive a high market price. It is anticipated that a key profitability driver for producers of aquaculture feed will be to minimize the use of fishmeal and fish oil while maintaining the performance and that utilizing novel ingredients such as algae-derived feed ingredients will also play an important role in feed producers' success. Following this line of arguments it is anticipated that fish farmers may face the need for strategic decisions of diversification of the farmed seafood targeting a high price or low price market; a diversification defined by the inclusion of marine ingredients including microalgae-derived ingredients, and the subsequent impact on feed price and fish meat quality[10].

2.2.2 Consumer markets for salmon

Consumer demand for salmon is closely linked to the prices for salmon. When salmon prices increase significantly (+30 %) as was the case in 2017, consumers purchased less of salmon products. The decline in consumer demand was most evident in the mature markets such as France and Germany, and even today the consumer demand in these markets are not back at the level of 2017. In Asian markets, salmon is considered as a delicatessen and demanded by more affluent and urban consumers. In China, for example, rising prices on salmon have not impacted demand, which seems to be continuously increasing.

It is not clear how a potentially higher price for salmon with above-average levels of EPA and DHA will be accepted by consumers. Lerøy Seafood claims that despite their salmon have higher levels of EPA and DHA than the average European farmed salmon, the consumers' willingness to pay an additional price premium remain uncertain. In the retail market it is a common practice that food suppliers and retailers trade is based on long-term contracts stating prices, qualities and volumes. When salmon prices fluctuate this is not reflected simultaneously or to the same degree in consumer prices due to the contracts formed between the retailer and salmon suppliers. This market mechanism shows the power of retailers and their possibilities of pushing price increases backwards upon their suppliers, which in turn, refuse to pay more for the feed in order to maintain their profit margins. Hence, it is clear that more expensive feed (which could include microalgae-derived ingredients) does not allow for a price premium on the salmon of its own, but the potentially higher costs from using microalgae could be justified if related to certifications for more sustainable production systems.

2.3 Global salmon feed production

The global production of feed for aquaculture (all species) was estimated at 40 million tons by 2016; hereof 11 % was for salmon, thus a global production of **feed for salmon amounting to 4 million tons[11].** The largest producers of salmon feed are Norway (1,739,000 tons); Chile (1,284,000 tons) and the UK (480,000 tons). Norway is the global leader in salmon feed production holding 45 % of the production. Most of the feed used for salmon farming is produced close to where the salmon farming takes place, figure 3.

[10] www.seafoodsource.com, 2015 based on Rabobank
[11] Marine Harvest, 2015

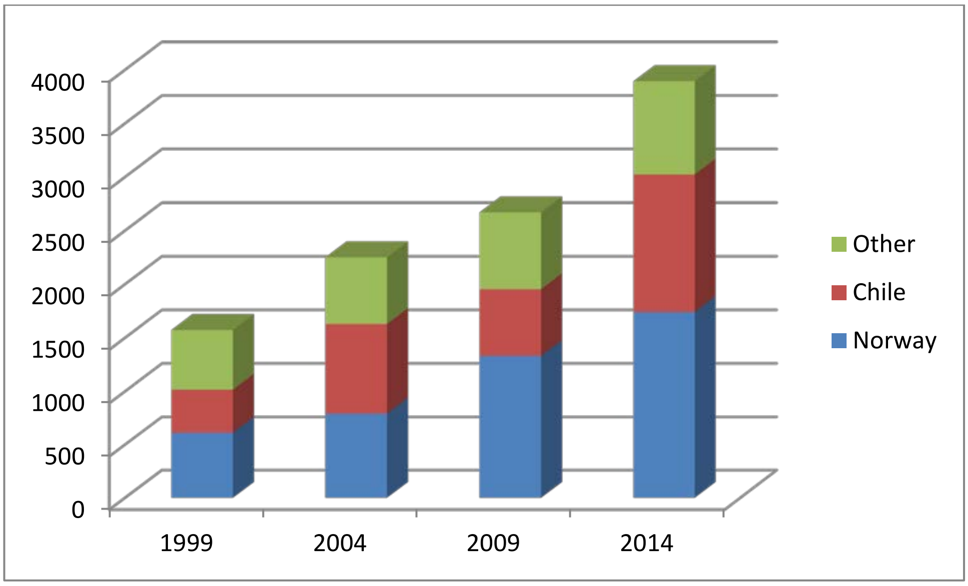

Figure 3: Production of salmon feed by country, 1999-2014

(Marine Harvest, 2015)

Manufacturing of fish feed is characterized as a consolidated industry dominated by large companies with global operations and, segmentation between companies producing feed primarily for salmonids and those who produce primarily feed for shrimps. The global top-three companies in the salmonid feed industry are Skretting (part of Nutreco), Cargill/EWOS and BioMar. Together, these companies hold 90% of the global market for salmonid feed. Marine Harvest is the company ranking fourth in global salmon feed production.

In collaboration with the Global Salmon Initiative (www.globalsalmoninitiative.org) the feed manufacturers are working to find alternative ingredients for salmon feed to reduce the dependency on fish meal and fish oil. The alternatives include using byproducts from the seafood industry, unsold catches, plant-based resources, and microalgae. According to FAO, 7 million tons of wild catch are destroyed/discarded as non-commercial harvest annually by commercial fisheries. This figure could have been converted into an annual fish oil quantity of 0.5 million tons, i.e. close to 80 % of the tonnage used in salmon and trout farming[12]. The salmon feed companies emphasize the need to secure transparency of the supply chain and the importance of demonstrating responsible use of resources as such actions contribute to future-proofing the industry and sustainability certification e.g. ASC or GNN.

Skretting/Nutreco

The company is headquartered in Norway and constituted a turnover of 2.4 billion USD in 2014. Skretting is part of the Dutch Nutreco group, specialized in feed for livestock and aquaculture. Skretting produces approx. 1.7 million tons of feed for several species of farmed fish and shrimps. The company holds 34 % of

[12] Marine Harvest, 2015

the global salmon feed production. Skretting has established an Aquaculture Research Centre in Norway with the purpose of diversifying its recipes beyond fish meal and fish oil[13]. Skretting/Nutreco has formed a joint-venture with DSM and Evonik in 2017 for producing microalgae-derived omega-3 fatty acids, and the lipids are approved for use in Europe. The microalgae production takes place in controlled land-based facilities and will be include in salmon feed using the brand name "MicroBalance"; a feed that is formulated to reduce the use of fish meal and fish oil[14].

Cargill/EWOS

Cargill/EWOS is claimed to be the biggest player[15]. Cargill, a major player in global feed and agribusiness, has entered the salmon feed industry through the acquisition of the Norwegian company Ewos in 2015. The acquisition strengthened Cargill's foothold in the global aquaculture feed industry and turned Cargill into a leading player in the salmon feed industry. Ewos now trades under the name Cargill Aqua Nutrition and is headquartered in Norway. Following the acquisition, Cargill will have access to seven feed manufacturing plants (three in Norway, and one each in Chile, Canada, Scotland and Vietnam) as well as two state-of-the-art R&D centers in Norway and Chile. Ewos produces more than 1.2 million tons of fish feed, primarily for salmon, and the company is among the biggest salmonid feed producers in the world[1]. The company emphasizes that sustainable sourcing of raw materials for the feed is already at the core of the business and will only become more important in the future[16].

BioMar

BioMar is headquatered in Denmark and is a global producer of fish feed. BioMar has production facilities in Denmark, Norway, Chile and the United Kingdom for manufacturing salmon feed and the company is counted among the global big-three for salmon feed production. In 2014, BioMar's turnover stood at 1.3 billion USD. BioMar has production facilities in Costa Rica and Turkey for feed for warm water species[17].

In 2016, BioMar introduced salmon feed with microalgae; a feed that was developed in collaboration with the large salmon producer Lerøy Seafood in Norway. The new feed contained a microalgae-derived ingredient high in EPA and DHA, "AlgaPrime DHA", supplied by TerraVia-Bunge. Because of the inclusion of the microalgae-derived ingredient "AlgaPrime DHA" it was claimed that the use of fish oil for salmon feed was reduced by 15-20 % for that particular salmon product. It was also claimed that the level of omega-3 fatty acids was higher in the flesh of this salmon compared to salmon fed a conventional diet based on fish oil. In the new feed, 7.5 % EPA/DHA was the minimum target whereas most of other salmon formations target 6 % EPA/DHA in the feed. The new feed was tested in a commercial scale at salmon farms in Norway, Chile and the UK. Since September 2016 BioMar has sold over 40,000 tons of the newly formulated feed, primarily to Lerøy Seafood. As of summer 2017, Lerøy Seafood has announced that the new feed will be

[13] IntraFish 2015 and www.skretting.com
[14] Skretting, October 2016
[15] www.feednavigator.com, May 2016
[16] www.ewos.com
[17] IntraFish 2015 and www.biomar.com

used for salmons at the 1 kg stage and until slaughtering; this indicating a success story for using microalgae-derived ingredients in fish feed[18].

Marine Harvest

In 2014, Marine Harvest expanded into the feed industry by establishing its own feed company; a strategy rooted in a decision to take more control of the most important cost centre in farming: the costs for feed. The company has a strong focus on increasing the use of novel lipid ingredients and protein sources which is in line with an implementation of the ASC certification[19]. It is claimed that several algal sources of DHA and EPA have been tested already, showing good nutritional and technical properties. Further it is claimed that the algal based omega-3 fatty acids are three times as expensive as fish oil, so inclusion in the salmon diets is not expected until the price of the algal based lipids become available in larger commercial volumes. During the first seven months of operation in 2014, the company managed to produce 128,000 tons feed for salmons at the Norwegian feed plant[20].

The global salmon industry (fish farmers and feed companies) is well positioned to further develop collaboration for a sustainable and future-proof industry with room for expansion. The joint forces rooted in the Global Salmon Initiative are clearly paving the way for a more sustainable salmon industry and especially the Initiative's encouragement to look for alternative sources of DHA and EPA are regarded to have a strong impact on the future demand for microalgae-derived ingredients[21].

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[18] https://www.feednavigator.com/Article/2017/04/25/Leroey-flags-up-use-of-microalgae-sourced-DHA-in-its-salmon-diets

[19] ASC: Aquaculture Stewardship Council; scheme promoting sustainable fish farming.

[20] www.marineharvest.com

[21] www.globalsalmoninitiative.org

Chapter 3 Formulating salmon feed

3.1 Salmons' need for essential fatty acids – EPA and DHA

Fish meal is the protein source traditionally used in aquaculture diets but it is considered as limited and expensive (compared to vegetable alternatives). Fish oil is the major natural source of healthy long chain EPA and DHA; both are fatty acids high in demand for human nutrition and for fish feed. The nutritional contents of algae are gaining importance as a renewable resource to substitute conventional ingredients in aquaculture diets[22]. A challenge in fish nutrition is to generate end products (seafood meat) with high levels of omega-3 fatty acids for the consumer, while reducing the use of fish oils[23]. Seafood is the only natural resource of LC-PUFAs (for humans) but, over 70 % of the global fish stocks are either over-exploited or depleted. This points to a need to find alternative ways of providing DHA and EPA for fish feed. Here, microalgae are considered as a more sustainable resource with a large yet unexploited potential for the production of DHA and EPA. In addition, algal meal is a rich source of other n-3 and n-6 fatty acids including ARA (arachidonic acid), and high quality protein, carotenoids as well as other micronutrients that are in demand by the aquaculture feed industry (and other industries as well).

It is claimed that the global aquaculture industry uses around 830,000 tons of fish oil (2017), and hereof approx. 70 % is for salmon feed[24] (= 581,000 tons of fish oil). This volume is equivalent of ca. 115,000 tons of EPA and DHA, thus the market that can be targeted with microalgae derived omega-3 fatty acids. (It is stated that the aquaculture industry would require around 240,000 tons of EPA/DHA to fulfil the needs in fish diets[25].

3.2 Ingredients used in salmon feed

3.2.1 Fish meal and fish oil

Raw materials for salmon feed include a range of animal and vegetable nutrient sources for supplying protein, fat and carbohydrates, supplemented by a selection of vitamins, minerals and additives. The purpose of supplementing nutrients is to ensure provision of essential nutrients such as omega 3 and omega 6, and an adequate supply of vitamins, minerals, colorants (for the skin and meat colour) and in some cases, also antibiotics and growth promoting substances. Fish oil serves two main purposes in salmon feed: lipids as energy for fish to grow, and it is the main marine source of long-chain omega-3 fatty acids (EPA and DHA) which are essential nutrients for salmon.

Fish meal and fish oil are key ingredients in compound feed for farmed fish such as salmon, and fish meal remains the optimal performing and best digestible protein source in fish diets. For salmon feed producers, minimizing the use of fish meal and fish oil while maintaining performance (i.e. fish growth, fish health and quality) is a key success factor and this creates opportunities and challenges for including proteins and fats from microalgae and other vegetable sources in fish feed.

[22] Yaakob et al, 2014
[23] Yaakob et al, 2014
[24] Ewos, 2013
[25] Undercurrentnews.com, 2014

Each year, approx. 5 million tons of fish meal and 1 million tons of fish oil are produced globally[26]. It is estimated that some 3-3.5 million tons of fish meal are used for aquaculture and this has been fairly constant over the last decade. The remaining 1.5-2 tons are used for feed for farm animals. Despite a growing demand for fish meal and fish oil for particularly the aquaculture industry, the global production of fish oil and meal is anticipated to level, figure 4. By 2015, prices for Peruvian fish oil were around 1,784 EUR per tons for crude oil and omega-3 fish oil, and for Chilean fish oil, prices were around 1,516 EUR per tons[27].

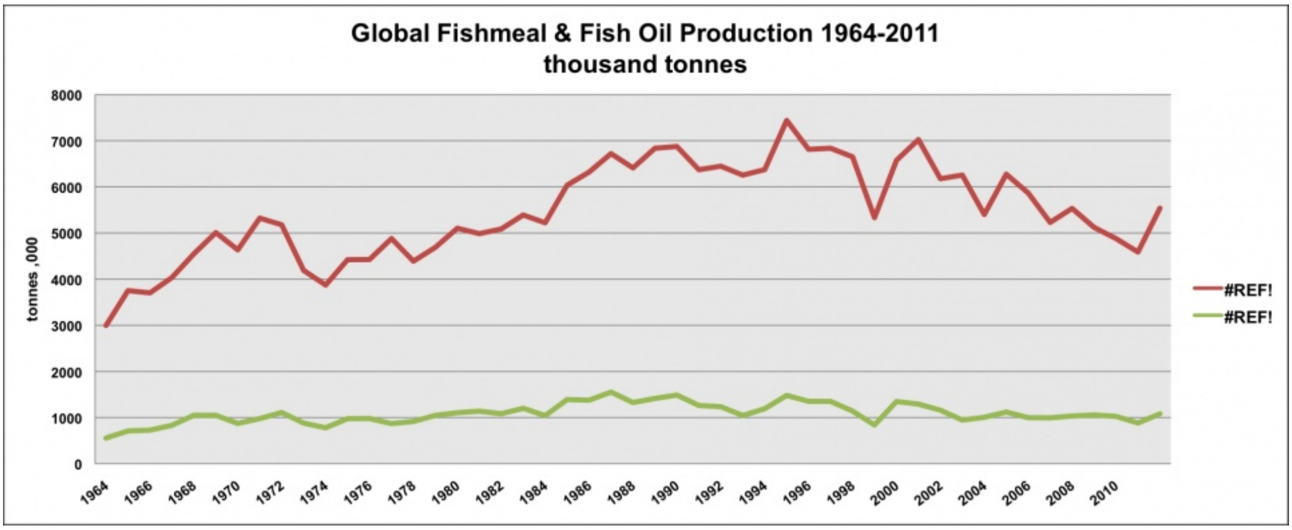

Figure 4: The global production of fish meal and fish oil from 1984 to 2011

(IFFO.net; red: fish meal, green: fish oil)

3.2.2 Alternatives to fish meal and fish oil

As natural resources for the production of fish meal and fish oil are finite, the need to find alternatives becomes evident. Figure 5 illustrates that there are options available for substituting fish meal, thus the protein-part of the salmon diet. Some of the alternatives showed in figure 5 are already widely used today. The fish feed manufacturer Ewos claimed that the company had increased its use of marine trimmings and byproducts in its feed to 31 % in 2013, up from 24 % in 2012[28]. Using the raw materials from figure 5 are not optimal sources of EPA and DHA, as the EPA and DHA mainly come from the fish oil. Microalgae-derived EPA and DHA can substitute fish oil, and this is already taking place in the global salmon feed industry (section 2.3).

[26] IFFO, 2015
[27] IntraFish, 2015
[28] www.feednavigator.com, April 2015

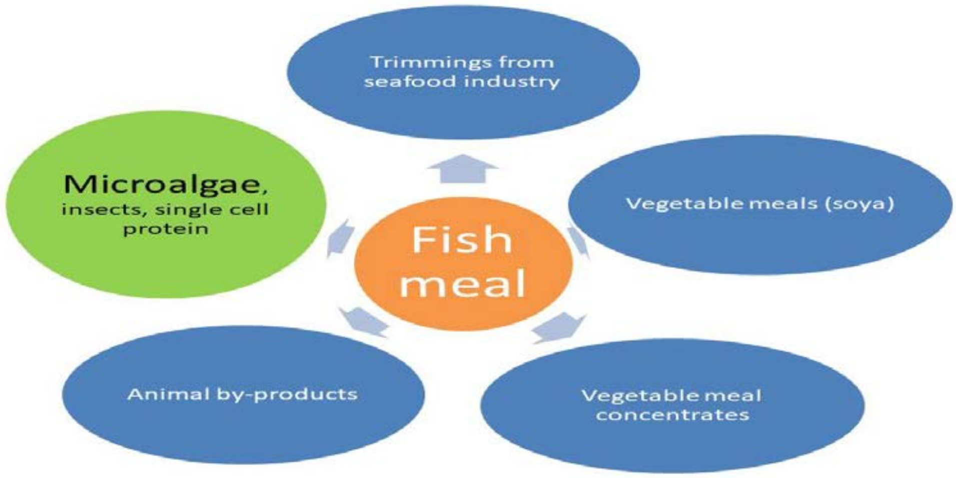

Figure 5: Current and future options for replacing fish meal with alternative protein sources

(IntraFish, 2015)

It is also clear that the balance between economics and nutrient supply plays a key role in identifying suitable alternatives to fish meal and fish oil. As prices for fish meal have increased the demand for cereals and vegetable protein for use in salmon feed has increased significantly, figure 6.

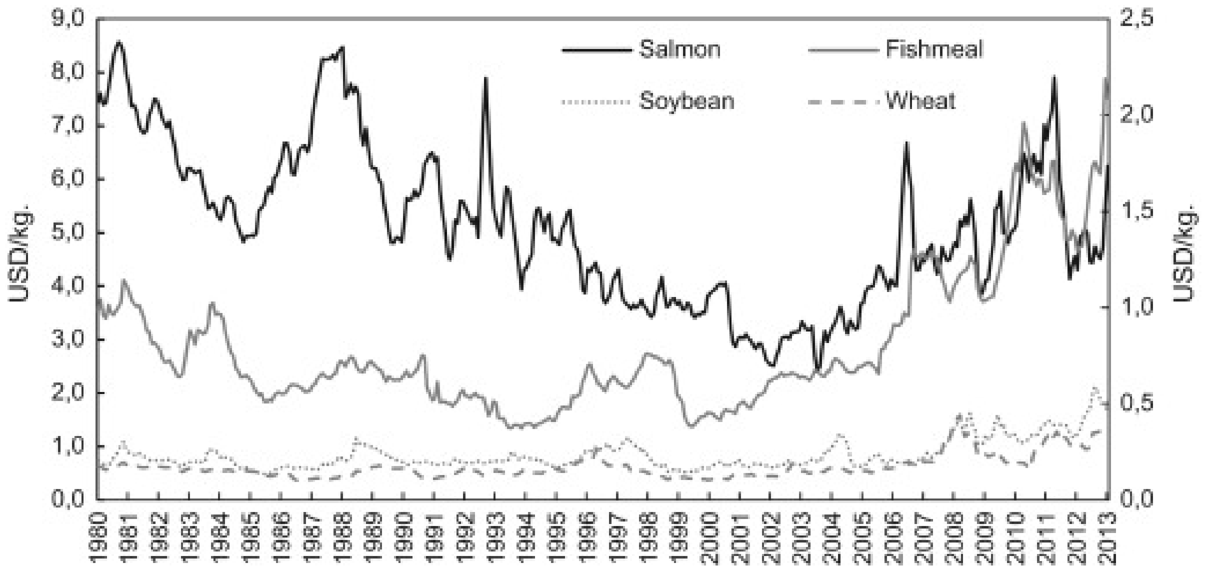

Figure 6: Development in prices for fish meal, soy protein, wheat and salmon

3.2.3 Plant-based ingredients

Among the important ingredients used to replace fish meal are, for example, soy bean meal, gluten meal, wheat gluten, peas and rapeseed meal. Fish oil is replaced by soybean oil, rapeseed oil, sunflower oil, linseed oil and other vegetable oils. This replacement strategy has resulted in fish feed diets with significantly reduced use of fish meal and fish oil, and at the same time, allowing for an expansion of the aquaculture production and leaving the challenge of finding competitive alternatives for EPA and DHA in diets for salmon open[29]. This is what makes microalgae interesting in the context of fish feed formulation as microalgae can produce selected LC-PUFAs.

Almost 70 % of the fish oil in salmon diets today is being replaced by vegetable oils. An increasing range of alternatives to fish oil are being offered in the market including microalgae and plant-based sources. Monsanto has introduced a GM soybean oil rich in the omega-3 fatty acid, stearidonic acid (SDA), which is said to be easier to convert to EPA in humans. Other biotech companies such as Dupont and BASF are pursuing similar strategies of developing GM canola and soybean plants that are high in EPA or DHA[30]. It is claimed that such plants are near-commercialization or already available in the market. But, it is also claimed that the use of ingredients made from such plants may be compromised by issues related to GMO and consumers' general acceptance of such plant-based ingredients.

When formulating fish feed diets, it is essential to assess the nutrients rather than raw materials in dietary and economic terms. This implies that it is the cost of nutrients rather than of raw materials that are determining whether a raw material has competitive performance in formulation of the fish feed. Following this, manufacturers of fish feed have listed a number of requirements for suppliers of raw materials[31]:

- The raw material (feed ingredient) has to be approved for use as feed;
- The protein content should be above 40 % for a protein ingredient;
- The ingredient should have a high digestibility;
- The feed ingredient should be in shelf-stable, uniform and milled format;
- Sufficient volumes (e.g. more than 1.000 tons) are to be supplied;
- Certifications responding to industry demands for traceability, non-GMO;
- If possible, certified as a sustainable product and
- Reasonable price

A critical shortcoming of crop plant proteins commonly used in fish feed is that they are low in certain amino acids such as lysine, threonine, methionine and tryptophan. In comparison, analyses of numerous microalgae have found that although there are significant variations, the microalgae generally contained all the essential amino acids required for a healthy fish diet[32]. In this perspective the options for substituting plant-based nutrients for microalgae in fish feed become clearer.

[29] Olsen, 2011
[30] www.feednavigator.com, April 2016
[31] Nørrelykke, 2015
[32] www.thefishsite.com, 2013

3.2.4 Microalgae in salmon feed

Microalgae can be used in salmon feed for several purposes, as outlined below. It must be underlined that no species can be used for all purposes, as for example only some microalgae produce EPA and DHA.

- As protein source for substituting fish meal;
- As source of calories and PUFAs for substituting fish oil;
- For adding color to the fish meat or skin; and/or
- For adding specific nutrients such as EPA and DHA or amino acids

As microalgae may contribute to salmon feed formula in more ways it is necessary to look at the microalgae species as the variety of species is enormous, and there are vast differences among the properties of the species in relation to adding to a salmon diet. Much research has been carried out across many countries to identify the optimal microalgae for the provision of specific nutrients. Research carried out in the FIMAFY project focused on the species *Nannochloropsis spp* as sources of EPA and DHA for salmon feed. Figure 7 shows examples of fish feed pellets produced with different proportions of dried *Chlorella* in substitution for fish meal.


Figure 7: Examples of experimental fish feed pellets containing different proportions of dried *Chlorella* in substitution for fish meal. (Retrieved from Centre for Sustainable Aquatic Research, Swansea University)

FAO suggests that fishmeal inclusion rates in salmon feeds which stood at 45 per cent in 1995 might fall to 12 % by 2020[33]. Calculations presented by Rabobank support the view, as presented in figure 8, where microalgae are included under “novel ingredients”. The figure shows that novel ingredients including microalgae could constitute around 10 % of the salmon feed formula in the future.

[33] Schmidt, 2016

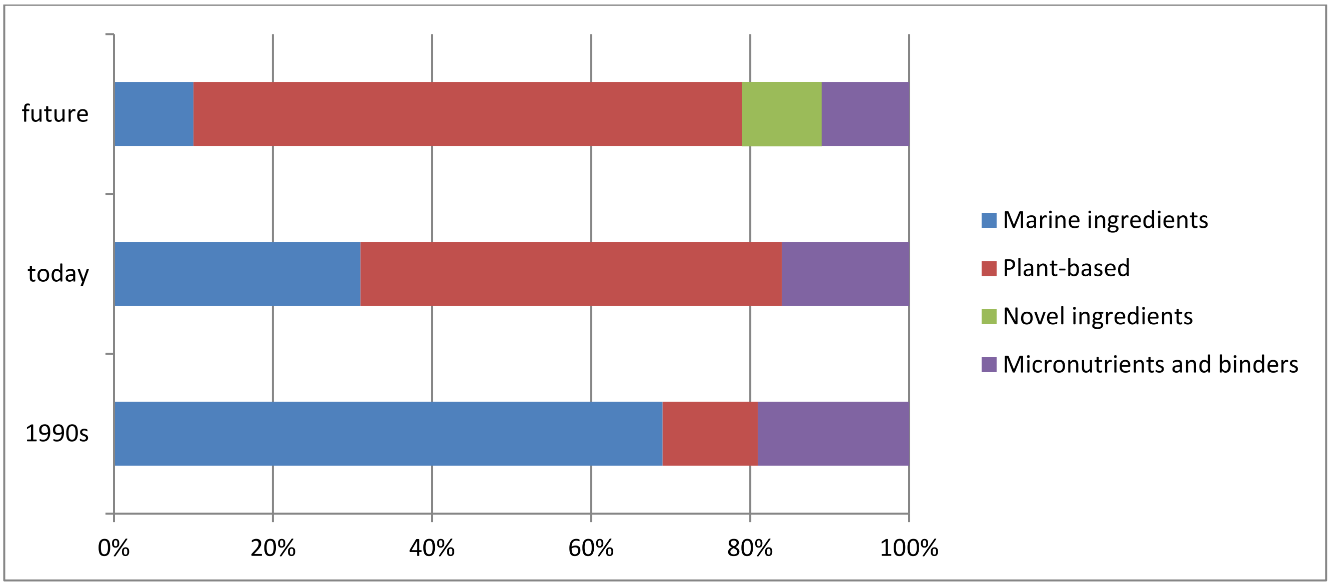

Figure 8: Development in salmon feed formulation

(Leffelaar J. 2016)

Research presented from NOFIMA supports the development illustrated in the figure 8. Feed composition for salmon production in Norway has changed significantly since 1990s. At that time fish meal constituted 65 % and fish oil 24 % of salmon feed. By 2014, recipes for salmon feed had changed to include 17 % fish meal and 9 % fish oil, at the expense of an increased use of vegetable raw materials (soya meal concentrates and sunflower meal)[34].

3.2.5 Assessing microalgae in economic terms

The price of microalgae is agreed between buyer and seller indicating that there is no "world market price" as there is for commodities. The price of microalgae depends on several factors as examples below present:

- Product – whole algal meal, extracted lipids or proteins, or other type of algae-product
- Quality – purity, destroyed cells /cracked algae cells
- Specifications – protein/fat ratios, DHA/EPA composition, amino acid composition etc.
- Stability - % dry matter, shelf-life
- Application – pharma, food, feed, technical or fuel grade applications
- Producer – country of origin, certifications

In addition to the list, the contractual agreement between buyer and seller has an impact on price. In the case of salmon feed, long-term agreements would be required. This is due to the fact that a feed manufacturer produces volumes of a specific type of feed in which the microalgae is used, and this feed is sold on contractual basis to the fish farmers. The example illustrates that the trading relationships between

[34] Marine Harvest, 2015

salmon farmer and feed supplier are based on long-term contractual agreement and this calls for a continuous supply of microalgae – if this ingredient is to be used in a specific type of salmon feed. Furthermore, this relationship also points to a critical factor: The entry barriers for a supplier of microalgae to the feed industry must be able to supply large quantities of defined qualities and continuously. Only microalgae producers that operate in an industrial scale would be in a position to enter into such contractual agreements.

Defining the price for microalgae may be related to the "quantity of product", i.e. price for 1 kg of microalgae or microalgae-derived ingredient, or the price may be viewed in relation to nutrients. This means that the price, hence the competitiveness of the microalgae, is assessed for the supply of nutrients per quantity. Researchers in Texas have developed a model for calculating prices for microalgae based on nutrients and, the researchers reached at conclusions stating that microalgae (*Chlorella* and *Nannochloris*) were price-competitive to fish meal (figure 9) and soy bean meal (figure 10).

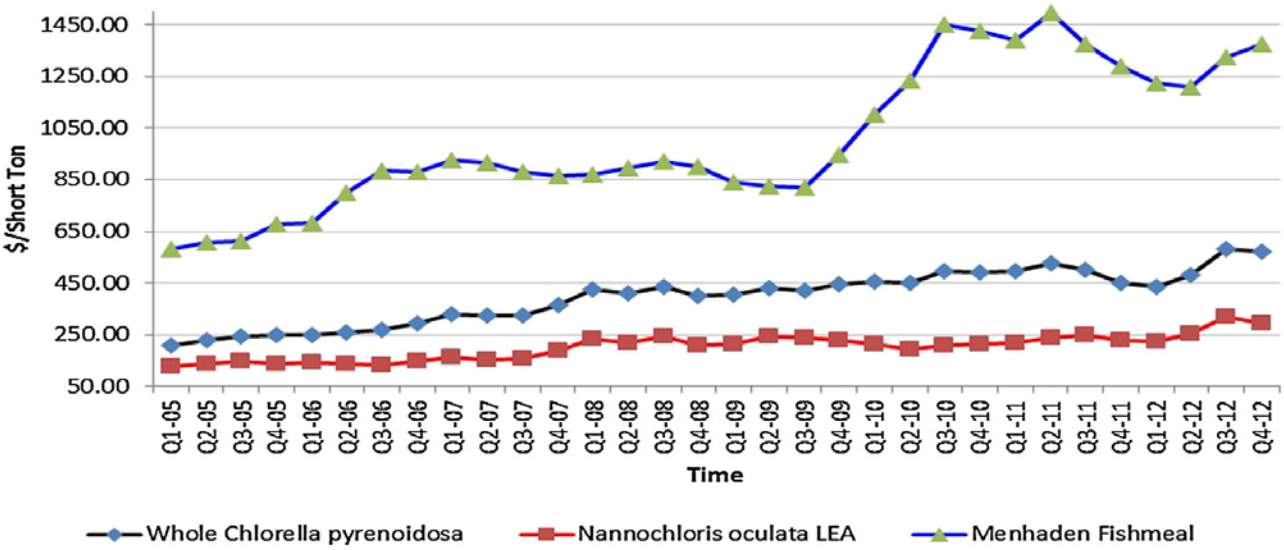

Figure 9: Value comparison of microalgae to fish meal

LEA = Lipid-extracted algae; Short ton = 907 kg. From Maisashvili et al, 2015

The researchers also showed that microalgae could be competitive to soy bean meal when priced according to their nutritional value[35], Figure 10. Here it is interesting to note that the LEA (lipid extracted *Nannochloropsis*) is more competitive as a protein source than soy bean meal. One conclusion to draw from this research is that if lipids are extracted from the *Nannochloropsis* and the microalgae is subsequently used as protein source the *Nannochloropsis* is valorized twice which is a significant contribution to increasing the viability of microalgae production.

[35] Maisashvili et al, 2015

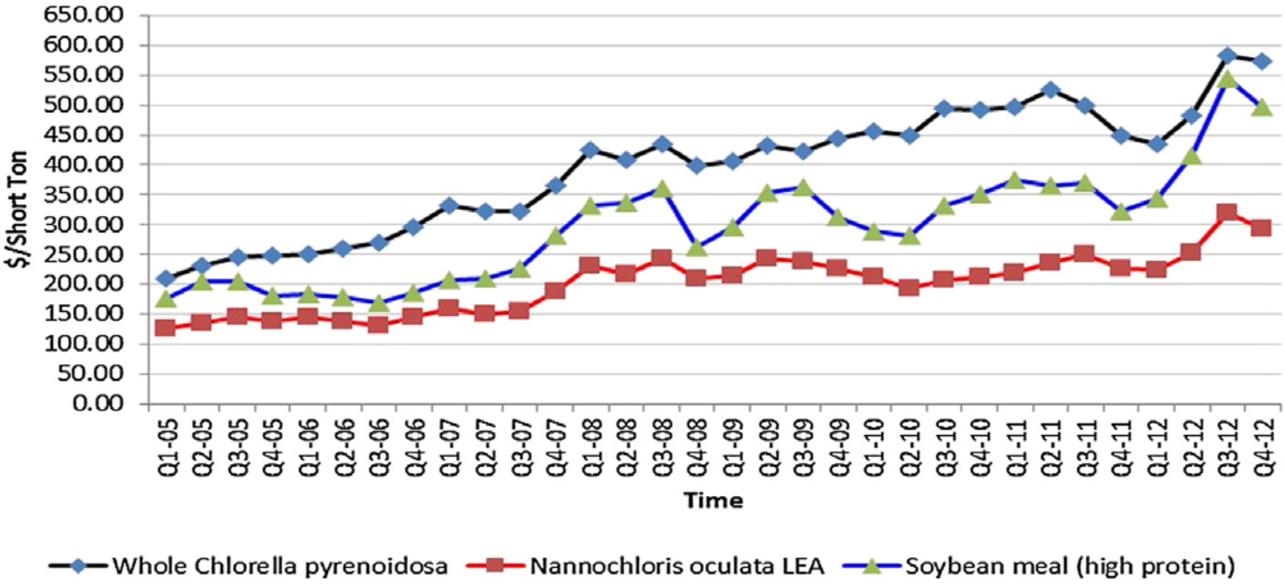

Figure 10: Value comparison of microalgae to soy bean meal

LEA = Lipid-extracted algae; Short ton = 907 kg. From Maisashvili et al, 2015

The conclusions about the pricing of microalgae in relation to nutrients are highly relevant for feed manufacturers. Recipes for compound feed, also for salmon, are developed to meet the fish's requirements for nutrients at a certain stage of life (fry or fish for slaughter). Following this, the feed manufacturer will optimize the recipes by choosing among the available ingredients (soy bean meal, fish meal, fish oils, wheat gluten, microalgae etc.) to reach the feed mix which addresses the fish's demand for nutrients AND at the same time is the economically most competitive feed offered from this manufacturer at this time. It is therefore essential that microalgae are both nutritious and economically competitive if microalgae and derived ingredients are to be used by the salmon feed manufacturers.

3.3 Inclusion rate for microalgae in salmon feed

When formulating a fish feed the particular attributes of each alga species must be carefully considered including the protein/amino acid profile, the lipid/PUFA profile, and pigment content. Therefore, the purpose of including algae into the formulation has to be clarified, as well as the cost-benefits of using algae compared to other feed sources must be considered. Price is one such dilemma. It is not the price per ton that is key issue; rather it is the price of the nutrients. This implies that the nutrient content of the feed ingredient has to be assessed according to protein and fat content i.e. the protein/fat ration (pro-fat ratio). Other quality parameters could be relevant to consider too; e.g. non-GMO feed or organic feed. It is clear that there are several factors to investigate before considering including microalgae in fish feed.

The inclusion rate for microalgae in fish feed depends on a number of factors such as:

- Prices of microalgae compared to other sources of nutrients;
- The supply situation for microalgae (certainty of supplies and consistent quality);
- Palatability and digestibility;
- Nutritional quality, especially the Pro-Fat ratio;
- Processing technology by fish feed manufacturers;

The key point is that the price for microalgae has to reach a level where the nutrients provided from the microalgae are price-competitive to nutrients from other ingredients. Trials from the FIMAFY project indicate a potential for inclusion of microalgae with cracked cell walls in salmon feed up to 20 %. For un-cracked microalgae, the FIMAFY results showed a decrease in digestibility at an inclusion rate of 10 %. Below are listed research findings about the inclusion rate of microalgae in fish feeds:

Research has proven that salmon diets containing up to 15 % *Schizochytrium* are highly palatable for Atlantic salmon (from 18 g start fish and up to salmon with a body weight of 1.2 kg) as well as highly digestible – especially in terms of protein and unsaturated fatty acids[36]. It was also demonstrated in this research that a diet containing up to 15 % *Schizochytrium* led to higher carcass yields compared to diets with land plant protein, and the content of PUFA (DHA) in the meat increased as the inclusion of microalgae increased. Hence, feeding microalgae (here *Schizochytrium*) has a clear positive impact on salmon meat quality and carcass yields.

Many trials have been performed to investigate how microalgae in diets for fish may impact fish growth performance and meat quality. In 2015, researchers demonstrated that marine algal products could be included in diets for Atlantic salmon by replacing 5-10 % of the protein normally provided by fish meal. It has also been demonstrated that *Chlorella* could be used in diets for Tilapia up to 50 % without an impact on fish performance[37].

Recent research carried out by NOFIMA and Alltech has shown that as much as 15 % of the fish meal and fish oil used in fish feed can be substituted by algae (such as *Schizochytrium*), and this substitution would have no negative impact on the growth of salmon, tilapia, trout and bass. Alltech has demonstrated that by feeding fish with a diet of fishmeal, vegetable protein and algae it is possible to reduce fish oil and marine resources to 1.2 pounds per one pound of fish produced[38].

Research carried out by the University of Swansea in the UK demonstrated that bio-meal from *Schizochytrium* (the by-product after the lipid fraction has been removed) with 9 % lipids could by mechanically rupturing the algae cell walls show an increased digestibility. This research group also demonstrated that by using combinations of technologies, the digestibility of *Chlorella* could be increased in feed for aquaculture. The researchers showed that if the algae biomass was only spray dried, the

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[36] Kousoulaki, 2015
[37] Maisashvili et at. 2015
[38] J. Stilts, 2014 and K. Kousoulaki, 2015

digestibility was 53 %, whereas a combination of spray-drying and ultrasonication increased digestibility to 63 %[39].

Trials with fish feed containing microalgae have shown that fish (Tilapia) fed diets with microalgae have a higher content of omega-3 and omega-6 fatty acids compared to fish feed without microalgae. Hence, it is claimed that the fish' absorption of omega-3 and omega-6 fatty acids is increased when the feed contains algae[40]. An additional benefit resulting from feeding fish with microalgae is the bigger production of mucous by the fish, and this again results in a lower disease rate and improved health status in the fish inventory. The above-mentioned trials all point to the possibilities of using microalgae in feed for farmed fish. The inclusion rate is thus closely linked to fish species, diet, and algae product.

As salmon farming is rooted in intensive production systems, the requirements for compound feed with a high feed conversion rate and sufficient supplies of nutrients are closely linked to the development in the salmon farming industry[41]. An increasing demand for salmon will push demand for compound feed up, and this would subsequently drive demand for nutrients including microalgae upwards.

[39] Shields & Lupatsch, 2012
[40] J. Stilts, 2014
[41] Leffelaar J., 2016

Chapter 4 Production of microalgae for DHA and EPA

4.1 Production and processing of microalgae

There are multiple ways to grow algae at commercial scale. Algae can also grow extremely well on marginal lands using salt water or wastewater, reducing impacts on valuable agricultural lands without competing with other industries for diminishing fresh water supplies[42]. Microalgae are commercially cultivated in a variety of methods as for example aerobically fermented systems where cultivation is performed in dark, mixing tanks using sugar as the main energy source for the algae. Algae may also be cultivated in open ponds, using either fresh- or saltwater, carbon dioxide and sunlight. Alternatively, they can be grown in brackish water or seawater in closed, transparent tubes called photo-bioreactors. A critical success factor for producing microalgae is to gain sufficient volume to benefit from economies of scale and to ensure that the microalgae product is not contaminated[43].

Species such as *Nannochloropsis* and *Schizochytrium* are rich in omega-3 fatty acids which are the lipids needed by the salmon feed industry for reducing the use of fish oil. These strains can be cultivated in a variety of ways and are produced in commercial scale today, table 1.

Table 1: Four commercial algal production systems for omega-3 fatty acid oils

Organism	**Region of production**	**Cultivation**	**System**	**Carbon source**	**Water source**	**Light source**
Schizochytrium	Brazil, USA	Heterotrophic	Fermentor	Sugar	(of sugar) fresh	(of sugar) solar
Nannochloropsis	USA	Phototrophic	Open pond	CO_2	Fresh	Solar
Nannochloropsis	USA	Phototrophic	Open pond	CO_2	Marine/brackish	Solar
Nannochloropsis	Europe	Phototrophic	Photobioreactor	CO_2	Marine/brackish	Artificial

(Moomaw et al, 2017)

It is known that *Nannochloropsis* is cultivated at a commercial scale using brackish water in outdoor ponds with added carbon dioxide (in Texas), and in photo-bioreactors using seawater and carbon dioxide at a geothermal power station in Iceland[44]. The species is regarded as a promising source of high-nutrient food and feed. It is 40 per cent protein by dry weight and 6 per cent EPA in a highly bio-available form.

The production price for microalgae depends on production system, price of input factors, the costs for processing, and the yield. Research from Norway suggests that for producing microalgae-derived EPA/DHA, the cheapest system (in 2013) was flat panels, figure 11. Access to sunlight and a lower cost level in general points to Spain as a more favorable location than the Netherlands. If other production systems were installed this situation may not be valid. It should also be noted that production costs for production in fermentation tanks were not part of the Norwegian analysis.

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[42] Carr, 2015

[43] Moomaw et al, 2017

[44] www.synbiobeta.com, October 2017

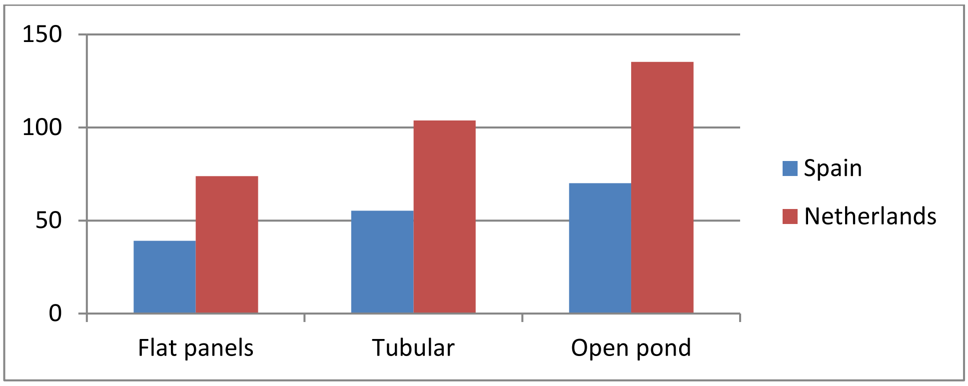

Figure 11: Production costs (USD/kg EPA/DHA) by type of production system and location, 2013

(Reitan, 2013)

Production of microalgae in commercial scale takes place in countries like USA, Israel, China, Brazil, Australia, and some European countries (Spain, the Netherlands and recently Denmark). It is assumed that microalgae production in the EU account for 5 % of the global microalgae production[45]. Figure 12 shows the most important regions for production of microalgae. Comparing the map of production from 2014 with the map from 2017 it is clear that a shift in production structure has occurred. Production in the US has declined and production in countries like Australia and Israel has increased. The focus in American production of microalgae has in a retrospective view been on microalgae for energy production but this has decreased due to less successful ventures and lack of markets (BIO, 2016). Other countries like Israel and Australia are advancing their production of microalgae in commercial scale operations to become important suppliers in a global context of microalgae *(Nannochloropsis)* for feed and nutritional supplements for humans (e.g. astaxanthines)[46].

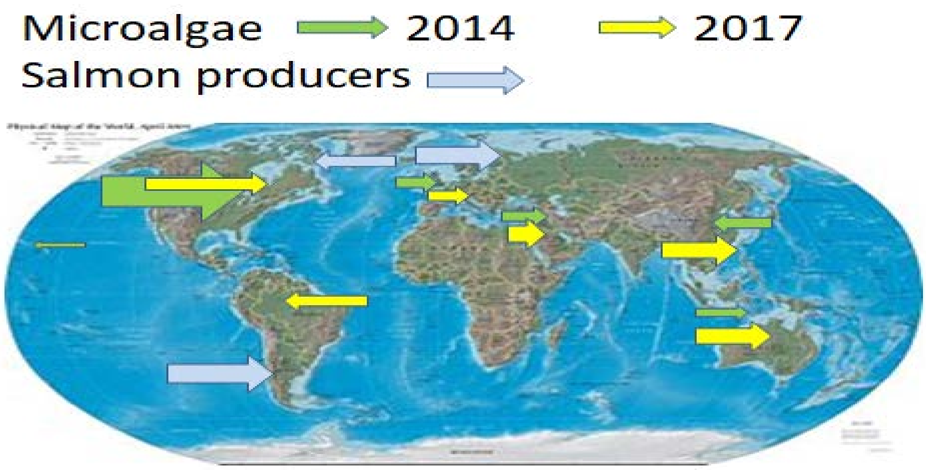

Figure 12: Major locations for microalgae productions. (Own elaboration)

[45] Enzing et al, 2014
[46] Mutter, 2013

Very limited information is available on the market size for microalgae and derived products. One report mentions the following market figures, table 2. Despite its lack of updated figures, table 2 shows that the production of whole algal meal is undertaken by a large number of companies and the relative value of the product is low compared to the price of the microalgae-derived ingredients. By 2005, Martek was the most important company in advanced manufacturing of omega-3 fatty acids based on microorganisms. This has changed since then.

Table 2: Global market figures of micro-algae based products, 2005

Current product based on microalgae	**Production volume, tons/year DW**	**Number of key producers**	**Value of production volume / yearly turnover (2005)**
Whole and dried algae meal for food and feed			
Spirulina	5,000 tons/year	+15 companies	40 million USD
Chlorella	2,000 tons/year	+70 companies	38 million USD
Microalgae derived ingredients for food and feed			
EPA / DHA	240 tons /year	+4 companies	300 million USD

(Enzing et al, 2014)

In a report from the UK, examples of prices for microalgae-derived products are presented, table 3. The table shows that there is a vast difference in price for food grade omega-3 lipids compared to prices for whole algal cells and microalgae products targeted at feed. It is also evident from the table, that production of EPA and DHA is undertaken by a wide range of companies (biotech companies, producers of microalgae, and producers of food-grade fish oil). Production of whole algal cells takes place in hot climates such as Hawaii and China. From the table 3 it can be concluded that the microalgae industry operates in markets where companies from other industries are also present, and that production of microalgae-based products takes place in many countries by the use of a variety of production systems.

Table 3: Prices for microalgae-derived products, 2011

Algae product	**Price estimates**	**Global market**	**Main players**
EPA/DHA omega-3 ingredients (food quality)	Marine oil concentrates 12-120 USD/kg; algal oils 70-150 USD/kg	1,3 million USD; 71,000 tons (2008)	Pronova, Croda, DSM, Blue Biotech International, Martek
Whole cells, *Spirulina*	5-150 EUR /kg		Blue Biotech International, Cyanotech, Hainan Simai Enterprises
Whole cells, *Chlorella*	18 USD/kg		Taiwan Chlorella Manufacturing Co.
Live microalgae paste for fish feed	210 USD/kg	EU: 40,000 L of paste	Blue Biotech International

(Schlarb-Ridley, 2011)

By using fermentation technology, large-scale algae cultivation can be established in developed and developing countries. The process can be automated and holds some competitive advantages compared to other algae cultivation processes in developed countries. Representatives of the microalgae industry claim that it is possible to cultivate (produce) the microalgae in large-scale plants using fermentation technology but that downstream processing still needs technology development to be economically feasible[47]. From salmon feed manufacturers it is revealed that large-scale fermentation of microalgae for production of omega-3 fatty acids is regarded as a future solution for provision of EPA and DHA for salmon feed[48]. This perception links well with the routines of trade and manufacturing of salmon feed manufacturers where stability in supply, expected quantities, and consistent quality of the microalgae-derived ingredient are key parameters for operating in the supply chain[49].

The system for producing microalgae-derived fatty acids includes the algae production (as explained above) and algae processing. Microalgae-biomass contains nearly 99.8-99.9 % water (i.e. 0.1-0.2 % dry matter). It is therefore crucial for the producer of microalgae to have an efficient dewatering infrastructure in order to increase the harvest of the microalgae. Such dewatering infrastructure could include microfiltration and centrifuge technologies. Results from the FIMAFY project demonstrated that the use of dewatering technology increased the level of dry matter to 2-5 % in contrast to 0.1-0.2 %. Following dewatering, several steps of downstream processing is required depending on the product and application, figure 13.

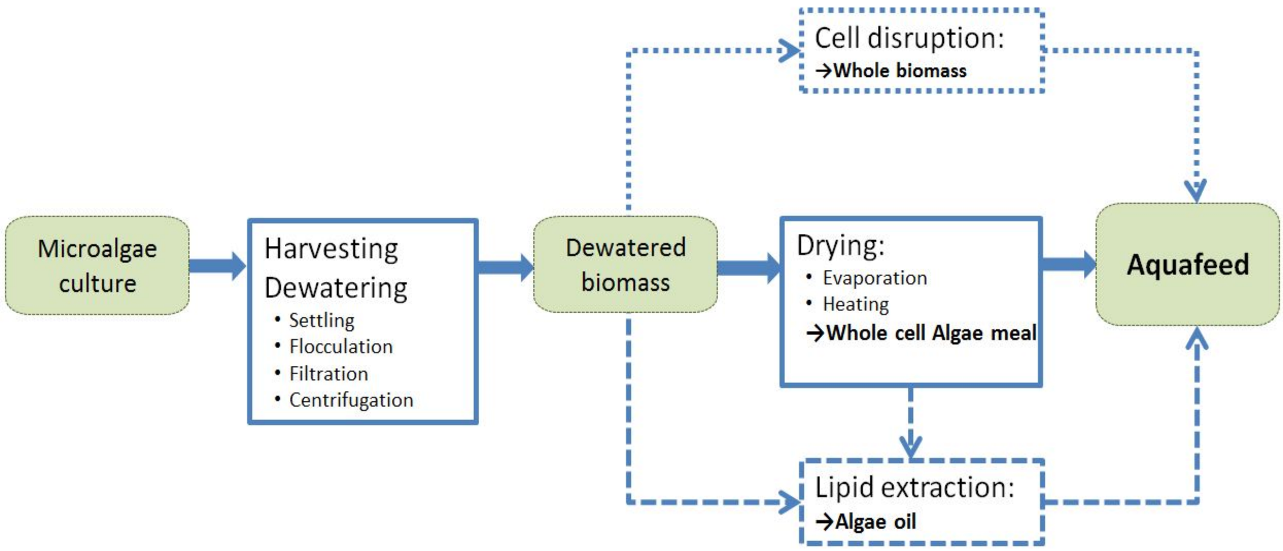

Figure 13: Schematic outline of the production process for microalgae-derived EPA and DHA

(Reitan, 2013)

[47] Kousoulaki, 2015 with possible reference to Alltech
[48] IntraFish, 2015
[49] Mutter, 2013

The processing of microalgae results in different types of products:

- Dried and granulated meal made from whole microalgae;
- Paste made from whole or cracked microalgae;
- Liquid products (as above);
- Microalgae-derived ingredients which are processed microalgae to retrieve specific compounds such as lipids, proteins or colorants, the ingredients may come in dried, semi-dried or liquid formats depending on the product.

Dried algal meal can be used directly in the fish feed, particularly if the cell wall of the algae is cracked (opened) to increase the accessibility of the nutrients. When microalgae are cultivated for the PUFAs, several steps of processing such as e.g. cracking, extraction, and concentration are needed[50]. Microalgae for use in fish feed must be appearing in a shelf-stable and transportable format, and with a functionality that meets the technical requirements of the feed mill equipment. Today, microalgae products available in commercial quantities are traded as paste or dried, granulated products.

4.2 Major producers of microalgae for fish feed

Production of microalgae in commercial scale is the starting point for becoming a supplier to the global fish feed industry. It is revealed that the global demand for DHA/EPA for use in fish feed is around 250,000 tons[51]. Given an estimated global production capacity of large companies in the microalgae-industry of around 220,000 tons for omega-3 fatty acids for humans and animals, there is a significant gap in the market supply of microalgae-derived omega-3 fatty acids. Only few suppliers of microalgae for fish feed operate with industrial capacity today but, the number of newcomers is increasing. The companies presented below are among the leaders in the global microalgae-derived omega-3 fatty acids industry.

ADM Inc.

ADM is a company headquartered in the USA and with its core business in the agribusiness and feed industries. In 2016 it was announced that ADM had developed a new dried microalgae meal high in omega-3 fatty acids and marketed under the brand "DHA Natur". The DHA Natur algae product is approved for use in feed including salmon feed in the EU and Chile. For the production, ADM has partnered with the US biotech company SGI (Synthetic Genomics Inc.) and the algae product is produced from fermentation. It is reported that the DHA Natur was to be tested in fish feed production in Norway and Chile in 2017 and with plans for scaling up the production[52]. Production capacity for DHA Natur is unknown. The production capacity is estimated at 20,000 tons, thus industrial scale[53].

[50] Kousoulaki, 2015
[51] IntraFish, 2015
[52] www.intrafish.com, 2016
[53] Estimated by IFAU, 2018

Alltech Inc.

Alltech Inc. is regarded as a pioneer within commercial-scale production of microalgae for fish feed. The algae activities were commenced in 2010. Alltech is headquartered in Kentucky (USA) and is a major animal nutrition company operating across several continents.

The goal of the microalgae production is to grow heterotrophic microalgae (most likely *Schizochytrium sp.*) rich in DHA, to reach a harvest-ready state in 12 days and, produce 15,000 tons annually. The production starts with an algae culture of 1.5 ml and within nine days this culture has developed into an algae culture of 265,000 liters which after final processing yields 20 tons of algae meal. The fat is not extracted and the cell walls are maintained which prevents oxidation. The dried algae meal is used in Alltech's compound feed and traded under the brand name *Aquate*. Alltech has built its pioneering algae facility in Kentucky and applies a fermentation technology using sugar for the production of algae. Tests of the production system have revealed that Alltech can produce algae with 35-40 % fat and a high content of DHA. The dried algae-meal had a fat content of 70 % and it is perceived that it is possible to achieve a fat content of 80 %, once the system is perfected. Alltech is convinced that similar results can be achieved with algae for the production of EPA[54]. Alltech claims that its set-up and process can either be replicated in small-sized plants around the world or it could be increased by 20-30 times and installed in connection to large fish feed production plants[55]. (www.alltech.com). In 2012, Alltech entered into agreement with the Norwegian research facility Nofima about documenting the (nutritional?) value of omega-3 from algae in the feed for salmon under Norwegian production conditions. The Norwegian company Produs Aqua (www.produsaqua.no) collaborates with Alltech on product optimization, marketing and sales of algae products in Norway and Faroe Islands. In 2014, Allltech has engaged in dialogue with the largest salmon producers (Marine Harvest and AquaChile) about constructing large-scale plants for the production of microalgae according to Alltech's technology and process. In 2018, a facility in Kentucky for production of 10,000 tons of microalgae-oil per year was closed. The closure was reasoned by economic aspects and available capacity at other facilities. The total production capacity across facilities is unknown, yet estimated at a volume of 80,000 tons[56].

Cellana Inc.

Cellana is an American company and a leading developer of algae-based bio-products. The company grows microalgae in commercial scale for production of its branded ReNew line of Omega-3 EPA and DHA oils[57]. The omega-3 oils are marketed to the fish feed industry and for human nutrition. The company also produces microalgae for biofuel. Cellana's production is based on a two-step system that couples closed photo-bioreactors with open ponds and ensures a consistent production. The production cycle is seven days from inoculation to harvest[58]. Cellana is one of the pioneers in the global microalgae industry with

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[54] Interview with Alltech, referred to at www.produsaqua.no 2015

[55] J. Stilts, 2014

[56] IFAU based on IntraFish (2015) where it is reported that Alltech plans production facilities for DHA of 80,000 tons.

[57] BIO, 2016

[58] http://www.biofuelsdigest.com/bdigest/2017/09/12/7-days-from-seed-to-harvest-cellana-and-the-rise-of-algae-in-a-world-seeking-more-faster-better/11/

production facilities in the USA incl. Hawaii, the Middle East, and Asia. The company's strategy is to construct and operate commercial facilities to produce these products through integrated algae-based bio-refineries[59]. By 2014, Cellana entered into collaboration with the Israeli company Galil Algae for the cultivation of *Nannochloropsis* for production of high value compounds for aquaculture. It has been reported that by 2017 the company was searching for commercial take-off agreement for 100,000 tons of algae-biomass, indicating that large-scale supplies were available to the market[60]. The production capacity for omega-3 fatty acids is unknown but it is of industrial scale.

DSM / Evonik

Announced in 2017, Evonik (a German company developing industrial biotech processes) and Royal DSM (Dutch bio-tech Company involved in cultivation of microorganisms) have formed a joint venture for the production and use of microalgae in fish feed. The joint venture trades under the name of **Veramaris**. The commercial-scale production facility will be established in the USA for the production of DHA and EPA rich microalgae, and this facility is anticipated to be operational as of 2019. The production capacity is believed to be 15 % of the global annual demand for EPA and DHA in salmon feed; around 25,000 tons of omega-3 fatty acids. By 2017 it was demonstrated in pilot-scale that the production of algae oils was possible and samples were provided to the feed industry. DSM has gained experience in production of high value compounds from microalgae as a supplier of dried whole microalgae with 18 % DHA content targeted at feed for pets, seafood and farm animals. DSM acquired in 2011[61] the US-based company Martek which was well-known for producing omega-3 fatty acids based on fermentation technology and cultivation of the microalgae *Schizochytrium*.

TerraVia /Corbion

TerraVia (formerly known as Solazyme) went bankrupt in 2017 and was later acquired by the Amsterdam-based company Corbion[62]. TerraVia operates two plants for the production of microalgae: one in Illinois, USA, and one in Brazil, the latter as a joint venture with Bunge (a major company in global agribusiness and soya). At the Brazilian plant, microalgae is produced in contained fermentation tanks and dried. The Brazilian facility has a capacity of 100,000 tons of algae oils per year. TerraVia produces healthy oils and lipids; whole algae-proteins; omega-3 based ingredients and other microalgae-derived products for food and feed (aquaculture, feed and pet food) purposes[63]. The final product is a whole algae ingredient containing 30 % DHA; marketed under the brand name "AlgaPrime". TerraVia mentions these criteria for promoting the sustainability of the "AlgaPrime" DHA:

[59] www.cellana.com
[60] http://cellana.com/products/renew-feed/
[61] www.nutraingredients.com, March 2013
[62] www.foodbusinessnews.com, august 2017
[63] BIO, 2016

- One ton of "AlgaPrime" DHA is equivalent of saving up to 40 tons of wild caught fish from the oceans on a DHA basis;
- DHA is 30 % in "AlgaPrime" which is three times higher than fish oil and higher than nearly all other oilseeds;
- "AlgaPrime" DHA can be produced in a matter of days in contrast to the long production time for DHA to be formed in the natural marine feed chain.

In 2017, TerraVia, BioMar and Lerøy Seafood entered into partnership for the production of salmon feed with a high content of DHA. The DHA was supplied by TerraVia and included in specially formulated diets made by BioMar. It is claimed that since 2016, BioMar has brought more than 40,000 tons of salmon feed made with microalgae into the market – mainly consumed by Lerøy Seafood but also for customers in Norway, Chile and the UK. This could indicate customers in the salmon farming industry[64]. In this context, BioMar has been a frontrunner for using microalgae in large-scale aquaculture feed production.

4.3 Trends in the microalgae industry

USA is the homestead of the microalgae industry and, the industry has developed significantly since its infancy in the late 1990's when the primary focus was on production of biofuels. Following the "great algae biofuel bubble" burst in 2012, the microalgae industry underwent a turn-around[65]. This resulted in a restructuring of the industry and many of the companies who were active in the biofuels industry turned towards other business options such as nutritional compounds for food and feed, lipids and proteins for feed, or development of technologies[66]. Also the production systems and processing technologies have developed significantly opening for opportunities for the microalgae industry to expand into more market sectors (food, feed, chemicals or energy).

A clear pattern is evident that producers of microalgae in commercial volumes are making use of either closed tanks and fermentation technology or large open-pond systems. The choice of production system is determined by climatic conditions, accessibility to feedstocks for the algae (e.g. waste water or side streams from biomass productions), end-product and, economics and investments. It is evident from research about companies in this industry that, in order to become economically viable the production must achieve volume, i.e. operate under the principles of economies of scale. For microalgae production this means to achieve as high throughput as possible (flow, harvest and processing yield) within a limited production system (e.g. barriers of tank system or number of ponds) to produce as much "product" as possible. Here, "product" refers to the marketable outcome of the microalgae production. In several cases, the company produces a range of products as this approach can contribute to increasing the exploitation rate of the microalgae; thus the possibilities for developing a profitable microalgae business, figure 14.

[64] BioMar et al, 2017
[65] Wesoff, 2017
[66] Carr, 2015

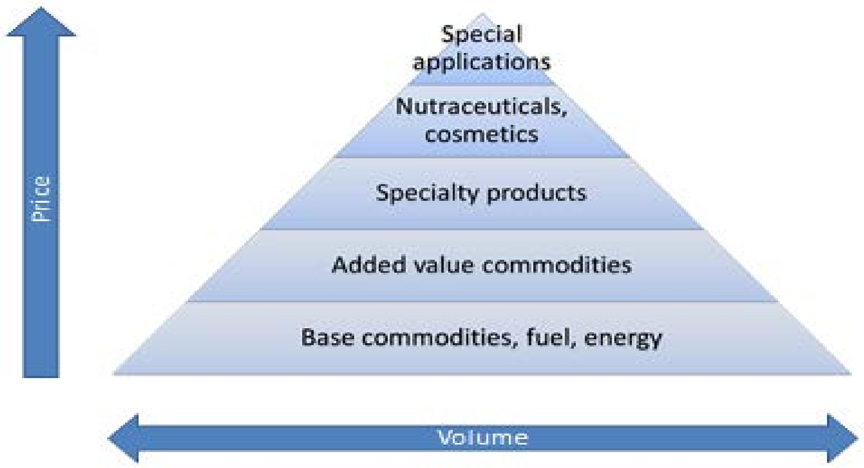

Figure 14: Increasing the exploitation rate of microalgae

(Own elaboration based on Schlarb-Ridley and Parker, 2013)

As an example, the company Cellana produces high value products (omega-3 fatty acids for human and animal nutrition), and microalgae for biofuels. Given the company's collaboration with Galil Algae for cultivation of *Nannochloropsis* for aquaculture, it could be anticipated that the business strategy of Cellana is turning towards a stronger emphasis on high value compounds compared to biofuels.

Reviewing of companies that produce microalgae in commercial scale – and particularly for use in fish feed – it becomes evident that large companies in the bio-tech industry are engaging with the algae industry through investments in joint ventures and acquisitions of microalgae producers. An example is the joint-venture between Bunge and Corbion to produce microalgae in Brazil under the name of TerraVia. The Dutch company DSM acquired a major American company Martek in 2011, an industrial bio-tech company using fermentation technologies for producing omega-3 fatty acids from microalgae and for use in infant food. As the microalgae industry matures and the production technologies become more advanced it is perceived that more joint ventures and investments are to be expected. The focus of such investments are anticipated to be microalgae-based productions of high value compounds with large and functioning markets as for example the market for omega-3 fatty acids or colorants (for food and cosmetics).

Chapter 5 Supply chains for microalgae in salmon feed

5.1 Dynamics of supply chains

On the one hand, demand for microalgae in fish feed is related to the need for finding alternatives to fish meal and fish oil for supplying essential fatty acids and proteins. On the other hand, rather few companies are in a position to supply large volumes of a microalgae product suitable for use in large-scale salmon feed manufacturing. This indicates two things: 1) that the supply chain for microalgae in fish feed exists and 2) it is a supply chain in development.

The supply chain for microalgae for use in salmon feed spans the players supplying the algae cultures to the consumers, figure 15. Providers of algae cultures offer cultures of defined species that are used by the algae growers and other bodies such as research facilities. The growers of microalgae form the next step in the supply chain, and they cultivate microalgae using a number of different production systems such as outdoor ponds or tubes; indoor systems based on large-scale tanks; or reactors. By harvesting and processing the microalgae, the growers turn the algae biomass into a shelf-stable and marketable product. Currently, a number of liquid, semi-dried (paste) and dried products are available in the market. The algae products are sold to producers of feed, and the feed companies supply feed to the salmon producers. Seafood processors then purchase and process the salmons for distribution via the retailers or restaurants, before the salmon product finally reaches the consumer market.

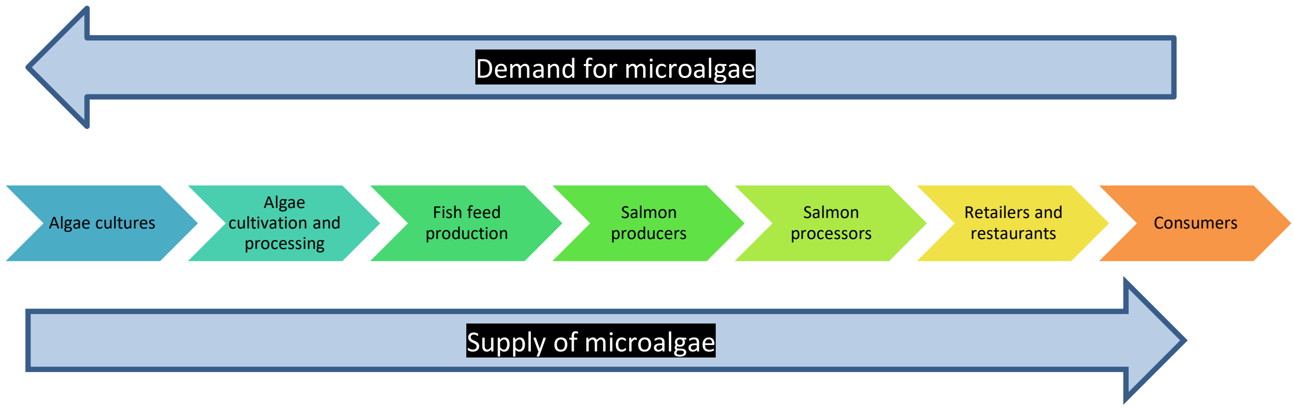

Figure 15: Principles of the supply chain for microalgae in fish feed, 2018

(Own elaboration, 2018)

The supply chain for microalgae for salmon feed is global. Producers of algae in commercial-scale operations are located in the United States, China, Australia, and a number of European countries (France, Spain, and the Netherlands). Salmon feed production takes place in Norway, the UK, Chile and North America. Some of the major salmon farmers are vertically integrated companies including feed production, salmon production, and for some, also processing of the seafood (particularly for shrimps and salmon).

Consumers form the last element in the global supply chain from microalgae to salmon meat, and the consumer market for salmon is already globalized. The major markets are France, Germany, the USA, and Asian market

Given the development in the microalgae industry towards larger and bio-tech oriented production, the global supplies of microalgae-derived compounds for use in salmon feed will increase and the market is expected to become less subtle to fluctuations in production volumes. This is an attractive development for large-scale salmon feed manufacturers as access to larger quantities of microalgae-derived ingredients will make the supply chain for such ingredients more resilient. In a long-term view, the outlook to a more resilient market and established supply chains may pave the way for investments in more large-scale microalgae productions, thus leading to an even more resilient supply chains.

The supply chain for microalgae derived ingredients for salmon feed is centered on the producer of microalgae and the feed manufacturer as the two core partners of the chain. It is the relationship between the feed manufacturer and the supplier of microalgae that tie in the other actors with this chain. This implies that the demands posed by the feed manufacturer for specific nutrients has implications for which microalgae producer(s) that will be included into the chain, hence the microalgae species to be produced.

In line with the maturation of the microalgae industry the demand for microalgae species and strains with commercial potential will be growing. This will drive the development and cultivation of algae strains that can meet the requirements from customers in industry; this being customers in the feed manufacturing industry, the food industry or in other industries (pharmaceutical, chemical or energy). The core issue is that more advanced technologies for cultivating and processing of microalgae and more resilient supply chains linking algae production with the market surely calls for improved algae strains. From literature reviews it is clear that the optimal strain of microalgae is a key requisite for a viable commercial production – but the strain is only one element of a complex production.

5.2 Sustainability as a driver for microalgae in salmon feed

The salmon farming industry is characterized by large companies with large fish farming operations, primarily located in the Norway, the UK, Canada and Chile. Concentrated salmon farming has an impact on the environment and fish health; two factors that are pushing the salmon farming industry to apply measures for increasing the sustainability of their operations. Particularly the link between depletion of fish meal and fish oil stocks and the possibilities for using alternative raw materials and ingredients in the salmon feed is an important element in the sustainability strategies of fish farmers and feed manufacturers[67].

Fish meal and fish oil can be produced from processing of by-products and trimmings from the seafood industry, and this contributes to reducing the impact from fish meal and oil production on fish stocks. An increased use of trimmings and by-products will thus improve the sustainability of the fish meal and oil industry and reduce the waste from the seafood industry[68]. The fish meal and fish oil industry has introduced its own certification scheme for demonstrating responsibly sourcing of raw materials from well-

[67] BioMar Sustainability Report
[68] www.feednavigator.com April 2016, quoting Nutreco

managed fisheries, safe and traceable production. By 2015, this certification scheme (IFFO RS) includes 110 certified factories across nine continents[69]. The changes in use of raw materials for manufacturing of fish meal and fish oils are relevant to include when the sustainability of fish meal and fish oil production is undertaken.

Some consumers have "sustainability" as a purchase criterion when buying seafood. Sustainability may refer to responsible production of farmed fish, responsible use of ingredients for fish feed, or production with reduced environmental footprint. In all these examples microalgae-derived nutrients or whole algal meal would meet the consumers' requirements for "sustainability". The Norwegian salmon producer Lerøy uses large quantities of microalgae-derived ingredients in the feed for salmon, and the company claims that this feeding strategy adds extra value to the salmon meat in the eyes of the consumer. The main argument here is the responsible production of salmon, but it is not certain if the consumers are willing to pay an additional premium for salmon fed on a more sustainable diet[70].

Internationally recognized certification schemes well-known in the food market have found their way into the seafood market. An example is the GlobalG.A.P.-related scheme, the **GGN Certified aquaculture**. The GGN Certification (https://aquaculture.ggn.org/en/) promotes sustainable aquaculture including salmon farming by addressing safe production, healthy food, social impact and especially ecological sustainable aquaculture production. It is the fish farmer, who is certified, and it is a requirement to processors and distributors that GNN certified products are clearly distinguishable from non-certified seafood products so that consumers clearly can identify the GNN certified products. Salmon products carrying the GNN certification are available in retailers such as Aldi (Germany), Kaufland (Germany, Poland, and Slovenia), Eroski (Spain), Hofer (Austria, Slovenia and Italy), figure 16.

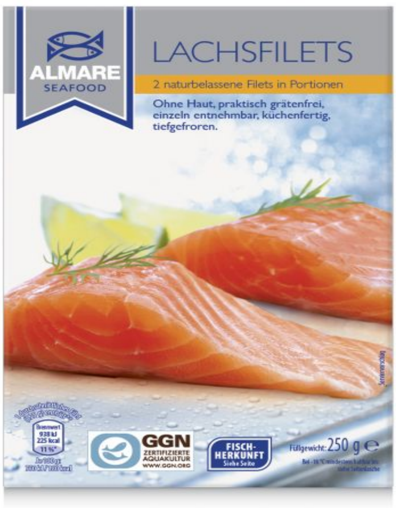

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Figure 16: Salmon products marketed with the GNN certification in German Aldi retail stores, 2018

[69] www.iffo.net
[70] BioMar Sustainabilty Report

The largest retail group in Japan, the AEON Group, has introduced a strategy for sustainable purchasing of seafood including salmon. It is stated that by 2020 all purchases of seafood must be certified as MSC for wild catches or ASC for farmed fish. In 2014, AEON introduced an ASC certified Atlantic salmon which was produced in collaboration with Lerøy Japan and WWF Japan, figure 17. The AEON Group has its own label for sustainable products and this label can also be applied for salmon.

Figure 17: ASC certified salmon in a Japanese AEON store, 2018

The examples and measures mentioned in this section point to a growing awareness about sustainable salmon production across the world. Given the fact that demand for salmon is forecasted to grow in the coming years and the need to produce more compound feed for salmon indicates expanding opportunities for including microalgae-derived ingredients in the feed. As EPA and DHA are essential nutrients to salmons it is clear that particularly production of microalgae which can provide such nutrients will experience increased demands from the major salmon feed producers.

5.3 Concluding remarks

Today, farmed salmon account for the majority of the salmon consumed in the World and salmon farming will continue to expand to meet the growing market demands. This outlook calls for identifying a pathway towards a sustainable intensification of the salmon production; thus an intensification that is rooted in the supply chain from feed ingredient to consumer market. The goal is to produce safe, affordable and nutritious food to an increasing number of consumers whose demands for salmon are not foreseen to decrease in the near future[71]. Salmon is an important source of omega-3 fatty acids that is essential for the human body, especially infant nutrition, so the global goal is expanded to include production of omega-3 rich salmon. In the light of the decreasing possibilities for using fish meal and fish oil for salmon feed, the

[71] Waite R. et al, 2014

need to find alternatives becomes strikingly clear and relevant. If salmon production is to meet the global demand collaboration, investments and technology development are needed to establish a route towards a sustainable intensification of the global salmon production.

Microalgae may very well enjoy a more profound role in this transition towards a more sustainable salmon-to-food chain, but other sources of nutrients for feeding salmon are also relevant in this context. Improving the competitiveness of microalgae products is essential for their potential success in a feed market where commodities like soy bean meal or wheat gluten set the agenda for trade. Improving the production systems for microalgae including development of strains and optimization of technologies for cultivation and processing are already implemented practices in the algae industry today.

The main companies in the salmon industry are very strong market players in their respective segments, i.e. in salmon farming and feed manufacturing. To meet the trading practices, standards and volumes of the salmon business a supplier of microalgae or microalgae-derived ingredients needs to be on similar terms, hence industrial-scale microalgae production is a necessary stepping stone for entering into the salmon feed supply chain. The microalgae industry shows strong signs of increasing “industrialization” and companies are selling the microalgae to customers in more segments: food, cosmetics, pharmaceuticals, ingredients, feed, chemicals or fuels. The palette of products keeps on widening as the technology develops and the global market demand matures. This is also true for the demand for microalgae-derived EPA and DHA in the salmon feed industry; a demand that can be stimulated by certification schemes targeted at sustainable salmon production.

It is anticipated that microalgae have the strongest role to play as providers of specialty nutrients such as PUFAs or pigments, rather than being considered in line with the commodity-based ingredients presently used in the salmon feed industry. Therefore, microalgae in relation to salmon feed will continue to appear as high-value products and by this, forming a niche market within the global market for fish feed. Having said this, it is also clear that the growing demand for salmon across the world will impact demand for fish meal and fish oil, and the need to find alternative feed sources remains strong. This is pointing to a continued interest from the feed manufacturing companies for using microalgae in feed for salmon.

Whether microalgae or other alternative feed sources will be the “fish meal and/or fish oil of the future” is uncertain but, one thing is certain: Performance of novel feed sources has to match the performance of fish meal and fish oil in terms of functionality, nutrition and economics; thus a triple-bottom line. But, when industrial-scale microalgae-ventures are being established and the supply chain for EPA/DHA in salmon feed is functioning there seems to be no doubts about the future perspectives for microalgae derived ingredients:

Microalgae are game-changers and will play a strong role for a continued transition towards a more sustainable salmon farming industry.

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And company websites as well