Chapter 4
Sustainable Aquafeed

Krishna R. Salin, V. V. Arun, C. Mohanakumaran Nair and James H. Tidwell

Abstract The global aquafeed production is expected to grow by 33% to 101.3 million tonnes by 2025 from the current (2015) estimate of 73 million tonnes, closely aligning with the targeted world aquaculture production of 101.8 million tonnes. Aquafeed industry mostly depends on the fish meal and fish oil from capture fisheries to supplement the essential nutrients for optimum growth performance in aquaculture. There has been an increasing trend to incorporate ingredients such as protein meals of plant and animal origin in aquafeeds as a consequence of the limited availability, fluctuating price and the growing concerns on the sustainability of fish meal and fish oil. The algal meal has been successfully incorporated in shrimp diets resulting in growth comparable to fishmeal suggesting potential replacement of fish meal even in shrimp larval feeds. The replacement of fish oil by 40–100% using various plant-based sources such as the marine microalgae, *Schizochytrium* in the diets of salmon, channel catfish, grouper and tilapia among others have also been reported. These results suggest the potential for the formulation of an aquafeed that is completely devoid of fishmeal and fish oil. However, one of the major concerns about the concept of 'vegetarian fish' is related to its taste and nutritional quality, particularly in the content of polyunsaturated fatty acids (PUFA). To sustain the desirable health benefits from fish intake in humans, reduced nutritional quality of farmed fish would demand higher dietary inclusion compared to the currently recommended levels. Genetically modified (GM) yeast, camelina, and metabolically engineered diatoms have been suggested to potentially replace fish oil in aquafeeds for improving the PUFA content in

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vegetarian fish. However, the ethical, environmental and economic costs of the use of GM organisms as an ingredient in aquafeed need to be evaluated for their recognition as a sustainable alternative in aquafeed.

Keywords Aquaculture feed · Vegetarian fish · Plant-based ingredients
Fish meal replacement · Fish oil

4.1 Introduction

World population is expected to reach 9.7 billion by 2050. Out of the current population of 7.3 billion, 780 million people are estimated to be undernourished in 2015 (SOFIA 2016). A major responsibility is vested with agriculture sector to feed such a huge population and ensure food and nutritional security in a sustainable way, which is a big challenge. Some of the major constraints for sustainable development of agriculture sector are climate change, global warming, scarcity of land and water, outbreaks, lowering oil price, regional conflicts, and instabilities and slow growth rate in global economy. Several strategies have been discussed for ending poverty and hunger, an ambitious target to be achieved by 2030 according to the Sustainable Development Goals set at the United Nations Sustainable Development Summit, 2015 (SOFIA 2016; UN 2015).

Proteins of animal origin in the diet help to alleviate malnutrition as they contain essential nutrients like vitamins, ω-3 fatty acids and minerals. In the next decade a 'nutrition transition' is predicted in developing countries from a calorie rich cereal diet to protein rich meat diet including beef, poultry, pig, sheep and fish, mostly driven by the increased rate of growth in per capita income there. This paradigm shift in consumption pattern would lead to an increased demand for meat products. Population growth and strengthening developed economies will also lead to a higher demand for meat products (OECD/FAO 2016).

4.2 Trends in Global Animal Meat Production

World beef production is expected to register a better average annual growth of 1.38% in the next decade (2015–2025) compared to the previous decade's growth rate of 0.82% (2005–2015). Similar upward trend is expected in the sheep meat production as well (1.44–1.98%). However, average growth rate in all other meat production sectors including pig (1.74–1.07%), poultry (3.19–1.51%) and fish (2.24–1.4%) will slow in the next decade. In general, overall meat production is projected to grow by 16% between 2013–2015 base period and 2025 (OECD\FAO 2016) (Fig. 4.1). However, it is expected that the production of sheep meat

Fig. 4.1 World meat production. *Data Source* OECD/FAO (2016)

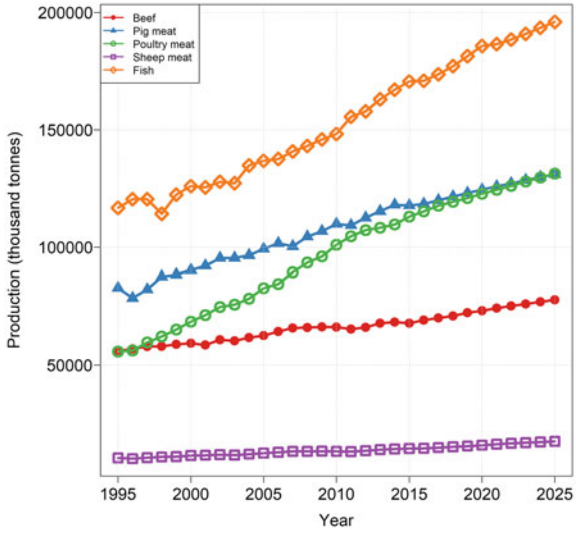
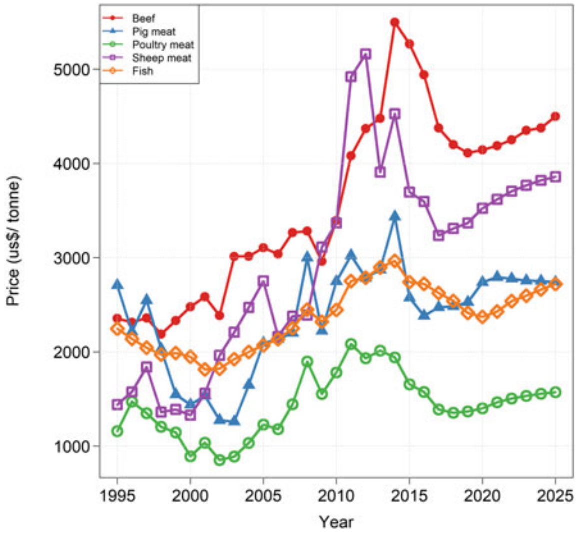


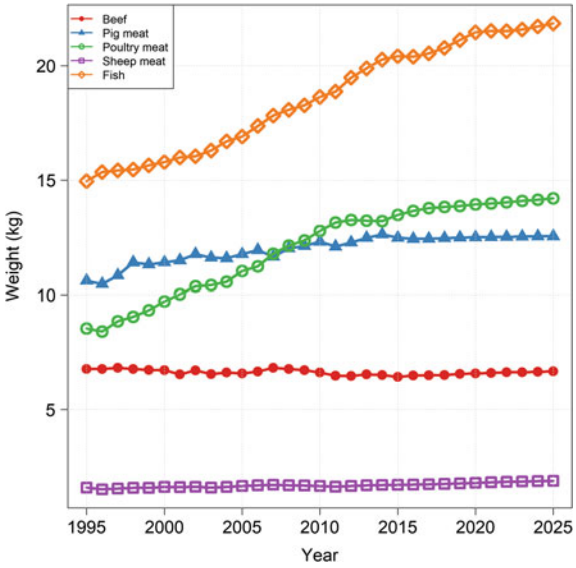
Fig. 4.2 Trend in price of world meat production. *Data Source* OECD/FAO (2016)



followed by poultry and fish will grow at 23.35, 19.02 and 17.39%, respectively during the same period.

The sluggish growth in global meat production can be correlated with the falling price of meat products (Fig. 4.2). Since the record hike in price of meat products observed in 2014, it is expected that that price will come down and stabilize around 2018–2019. Thereafter the price will again start to rise albeit in a slow pace. Beef, poultry and fish prices are projected to show negative average annual growth rates (−1.47, −0.42 and −0.03, respectively) in the next decade (2015–2025) compared

Fig. 4.3 World per capita meat consumption. *Data Source* OECD/FAO (2016)



to the 2005–2015 period. This softening of price, particularly because of strengthening of the dollar, El Niño effect, and slow down of emerging markets will positively affect the per capita consumption of meat products (Fig. 4.3) in the coming years (OECD/FAO 2016). Further lowering of price expected for meat products in the next decade may be due to a lower demand for meat products that can be attributed to economic difficulties in Russia, Brazil, China and Japan. However, strengthening USA and European economies will have a positive impact on the demand for meat products (OECD/FAO 2016).

4.3 Health Benefits of Fish

The human consumption of meat products in the next decade will be influenced by their price, the potential health benefits and risks as well as their perceived sustainability. The primary benefit of consuming meat lies in its nutritional composition. Animal meat continues to be the best source of dietary protein, fats, cholesterol, vitamins and minerals. However, there is still widespread discussion on the actual health benefits of many meat products. Several recent studies have shown a positive association between the consumption of red meat or processed meat and chronic diseases such as cancer, heart diseases and diabetes (De Smet and Vossen 2016; Kushi et al. 2006). In this context, fish is regarded as one of the most beneficial and safe animal meat products for human consumption (Photo 4.1).

The health benefits of fish are many. Fish is well known for its balanced composition of essential amino acids. Fish is a good source of vitamins especially

Photo 4.1 Seafood forms an essential part of a healthy diet. Photo by K.R. Salin

Photo 4.2 Appealing seafood display at a restaurant in Wuhan, China. Photo by K.R. Salin

vitamin D, A and B. Fish provides minerals such as calcium, iodine, zinc, iron and selenium. It is suggested that fish rich in ω-3 fatty acids may reduce the chances of cardiovascular diseases (Kushi et al. 2006). Studies conducted in animals indicate that fish oil suppresses the incidences of cancer (Kushi et al. 2006). Fish oil also helps in controlling obesity in human beings. (Wong et al. 2013). These positive health attributes are expected to lead to a surge in fish consumption in the next decade and place fish at an advantage, encouraging a substantial shift in consumer preference towards fish over the relatively inexpensive poultry products (Photo 4.2).

4.4 Paradigm Shift in Aquaculture Feed Sector

Boundless opportunities exist for the seafood sector as the world draws itself into a 'global village' with rapid urbanization, and the emergence of middle class population as major consumer segment in many parts of the world. Capture fisheries production has been stagnated at around 90 million tonnes since the 1990s (Fig. 4.4). However, the total fisheries sector (capture and aquaculture) has been growing at 3.2% since 1961 and has outpaced the global population growth with per capita consumption of fishery products reaching 20 kg in 2015 (SOFIA 2016). This remarkable growth has been achieved primarily through the contribution of aquaculture, one of the fastest growing food production sectors in the world. In the last decade (2006–2015), aquaculture has grown at an average annual rate of 5.53% but it is expected to slow to around 3% in the next decade. It is estimated that aquaculture has to grow by 33% in terms of production volume from 75.9 million tonnes (OECD/FAO 2016) in the next ten years to meet the projected additional output of nearly 25 million tonnes to reach a total production of 101 million tonnes by 2025 (Fig. 4.4).

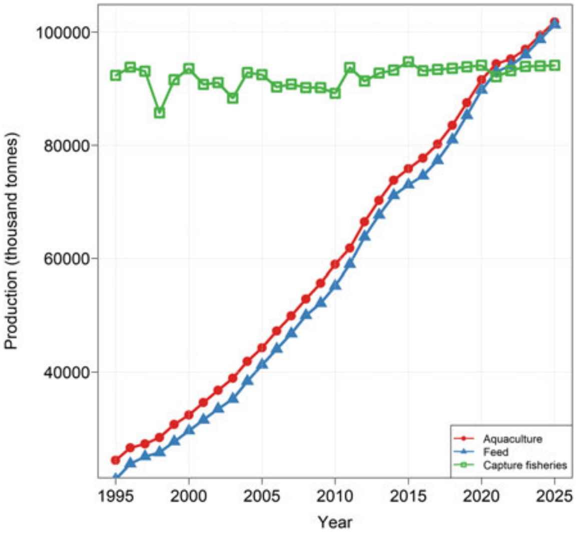


Fig. 4.4 Global production of fish from capture fisheries and aquaculture, and requirement of feed. *Data Source* OECD/FAO (2016)

However, key challenges that arise in the context of a sustainable annual growth rate of aquaculture include:

- The fishmeal challenge: how sustainable is to catch wild fish to feed the farmed fish?
- How to address the issue of carnivorous fish that are produced at a higher environmental and economic cost compared to the herbivores?
- How sustainable is the transition from fish meal to plant based ingredients in aquafeed?
- How to ensure and maintain nutritional superiority of aquafeeds with plant based ingredients in place of fish meal?
- How biotechnology can be applied to ensure sustainability of the aquafeed industry?

One of the major segments of the aquaculture production system is supplementary feed which accounts for over 60% of the total cost of production. Supplementary feeds provide the required macronutrients (protein and lipids) while relying on natural foods from the culture system (usually ponds) to supply expensive micronutrients (vitamins and minerals). Availability of good quality of feed at adequate volumes is essential to achieve the targeted aquaculture production. Over the past few decades the aquafeed industry has transformed from the traditional feeding using trash fish and rice bran/oil cake mixture to the high quality compounded pelleted feeds (Photos 4.3 and 4.4). Current level of feed technology addresses the nutritional requirement for farmed aquatic animals to the level of individual amino acids, vitamins and mineral requirements (complete feeds). In

Photo 4.3 Intensive raceway farms like this in Shanghai, China are based on high feeding rates of high quality feed. Photo by K.R. Salin

Photo 4.4 Pellet feed used in aquaculture. Photo by K.R. Salin

view of the aqua feed production over the previous decade (2006–2015) that has recorded an average annual growth rate of 5.9% and its projected growth rate of 3.3% in the next decade (2016–2025), the total feed requirement in 2025 for aquaculture sector is estimated to be 101 million tonnes (Fig. 4.4).

4.5 Feed Ingredients—The Fish Meal and Fish Oil Dilemma

One of the major constraints for aquafeed production is the limited availability of feed ingredients and their booming prices. The inclusion of fish meal and fish oil in aquafeeds and their positive impact on the composition of the final product are primarily responsible for the health benefits of aquaculture products compared to other meat products (Henriques et al. 2014). Rational use of fish meal and fish oil plays a major role in maintaining efficient feed conversion ratios (FCR) and optimum growth in aquatic organisms (Photo 4.5).

Fish meal is prepared by cooking, pressing, drying and milling of low value marine fishes, particularly the small pelagic fish that are not suitable for human consumption, and fish processing waste. Fish oil is prepared by centrifuging the press liquor obtained after fish meal production. Fish meal generally contains 60–72% protein depending upon the raw material used (Shepherd and Jackson 2013) and is a high quality protein with a uniquely balanced amino acid

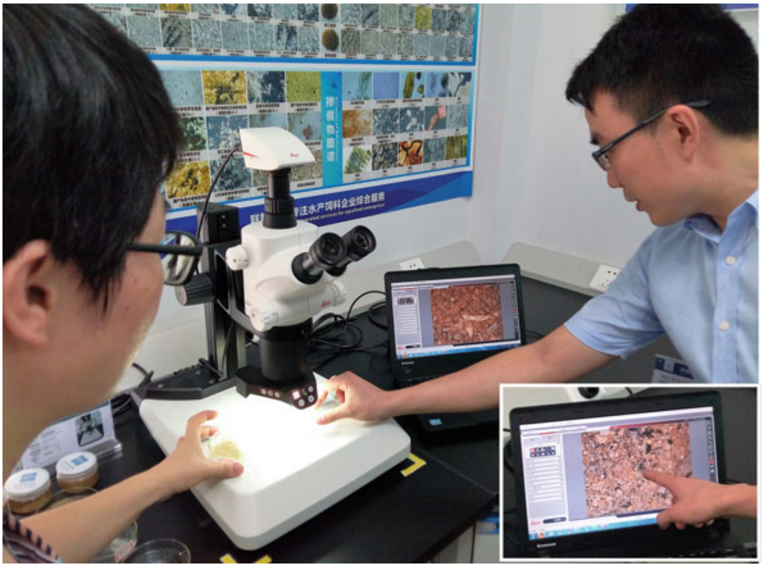


Photo 4.5 The quality of fish meal used in aquafeeds is critical. Microscopic examination can help to select the best quality fish meal for feed manufacturing process. Photo by K.R. Salin

composition, including all the essential amino acids. This property makes fish meal an ideal ingredient in aquatic and terrestrial animal feeds, which ensures the best growth, survival and reproduction in animals, compared to most plant based protein sources. Fish meal is a very good source of nucleotides, essential fatty acids and phospholipids. It also contains minerals like calcium, phosphorus, magnesium, zinc, manganese, selenium, iodine, molybdenum and chromium, in addition to the water soluble and fat soluble vitamins. Fish oil is a natural source of essential polyunsaturated fatty acids like eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA).

In 1960, the poultry and pig industries consumed as much as 98% of the global fish meal supply. However, as the salmon farming techniques became popular in temperate countries the aquaculture industry was using about 10% of the global supply of the fish meal by 1980 (Shepherd and Jackson 2013). This trend continued with the rapid expansion of aquaculture sector, while the terrestrial animal feeds moved closer to plant based ingredients. In 2012, aquafeed industry consumed almost 68 and 74% of the global fish meal and fish oil produced, respectively (Mallison 2013).

Global fish meal production increased over time until 1994 with a peak production of 7.5 million tonnes. Fish oil production also reached its peak of 1.5 million tonnes by 1994 (Fig. 4.5). The fish meal and fish oil production declined thereafter, although with inter-annual fluctuations. The lowest production levels of fish meal were observed during 1998, 2003, 2010 and 2014 with volumes of 5.3, 5.5, 4.4 and 4.1 million tonnes, respectively. Consequently, fish oil production was

Fig. 4.5 Global fishmeal and fish oil production. *Data Source* OECD/FAO (2016)

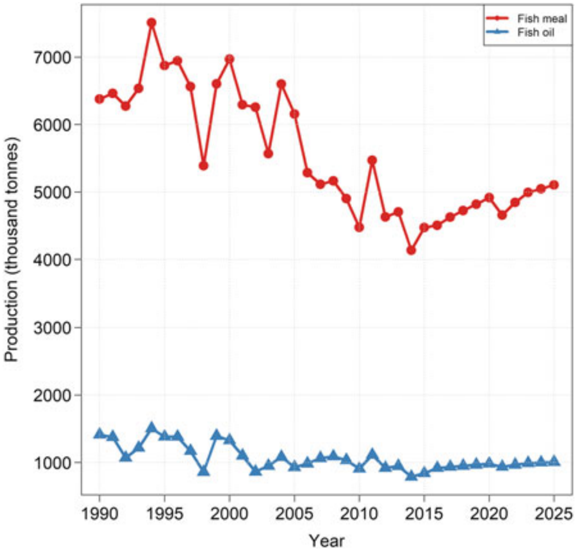
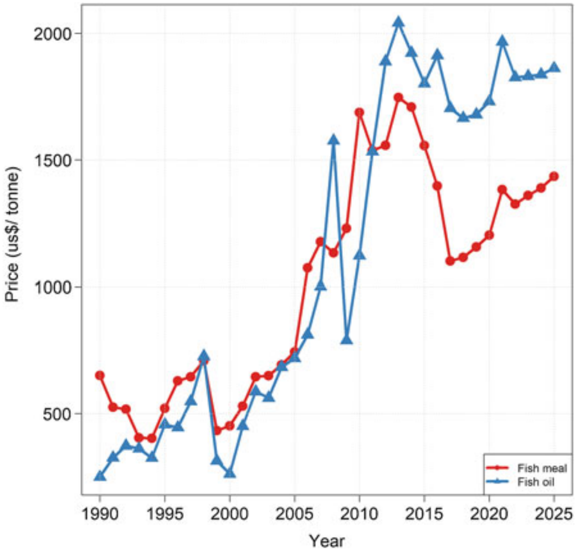


Fig. 4.6 Global fishmeal and fish oil price. *Data Source* OECD/FAO (2016)



also low during 1998, 2003, 2010 and 2014 with 0.85, 0.86, 0.9 and 0.78 million tonnes, respectively. Over the last decade (2006–2015) the total fish meal and fish oil production have shown negative annual growth rates of −2.57 and −0.29%, respectively.

4.6 Impact of Fish Meal and Fish Oil on Feed Cost

The cost of aquafeed depends to a great extent on the price of fish meal and fish oil. The average annual price of fish meal was the lowest in 1994 and 1999 at 403 and 433 US$/tonne, respectively (Fig. 4.6). Since 1999 the price had continued to increase reaching 1230 US$/tonne in 2009. However, fish meal prices surged steeply thereafter with 1687 US$/tonne in 2010 and a peak of 1747 US$/tonne in 2013. In the past decade (2006–2015) fish meal price increased at an average annual growth rate of 8.94%.

A similar trend is also observed in fish oil price where the lowest price levels of 325 and 262 US$/tonne were observed during 1994, 2000, respectively. The price of fish oil increased at a slow pace until 2002 and gained momentum thereafter. However, after 2010 there was a sudden spike reaching a peak in 2014 (1923 US$/tonne). It is also interesting to note that the annual average fish meal prices were higher than fish oil until 2010, when fish oil became more expensive than fish meal.

4.7 Status of the Major Fish Stocks Supporting Fish Meal and Oil

During 2013–2015 period nearly 17% of the total capture fisheries was utilized for fish meal production (SOFIA 2016). Fish meal is mainly derived from small pelagic fish with high oil content. These fish stocks are often characterized by early maturation and high fecundity. The species used for reduction to fish meal depend on the region of production. For example, the European fish meal production is mainly from fish such as capelin (*Mallotus villosus*), blue whiting (*Micromesistius poutassou*), small sand eel (*Ammodytes tobianus*) and Norway pout (*Trisopterus esmarki*). These species comprised 35% of the total fish meal requirement of the European feed industry with the rest imported from South America (20%), derived from Antarctic krill or, from food fish processing waste (Huntington and Hasan 2009).

A major global producer of fish meal is South America. Peruvian anchovy (*Engraulis ringens*) and Chilean jack mackerel (*Trachurus murphyi*) dominate the South American fish meal industry. Alaska Pollock (*Theragra chalcogramma*), Argentine hake (*Merluccius hubbsi*) and Southern blue whiting (*Micromesistius australis*) are also reduced to fish meal in South America. In Africa small pelagic fishes are mainly used for direct human consumption. South Africa has a fish meal industry dominated by European pilchard (*Sardina pilchardus*), other sardines and European anchovy (*Engraulis encrasicolus*) (Huntington and Hasan 2009).

A time series analysis of the major pelagic fish stocks which contribute to fish oil and fish meal production shows wide inter-annual fluctuations (Fig. 4.7). Over the past quarter of a century (1990–2014) small pelagic fish capture production was dominated by three species, namely Peruvian anchovy, Alaska pollock, and Chilean jack mackerel with shares of 45, 23 and 13%, respectively. Together these three species contributed 81% of the small pelagic fish captured for fish meal and fish oil. It is evident that Peruvian anchovy production account for much of the variation in small pelagic fish production. During the past 25 year, Peruvian anchovy peaked at 12.5 million tonnes in 1994, with its lowest point in 1998 (1.7 million tonnes), followed by a continuous decline. The catch of Alaska Pollock had shown a declining trend till 2000 thereafter maintaining around 2.8 million tonnes till 2010. However, this catch has improved thereafter showing some signs of recovery. The Chilean jack mackerel had also shown a strong decreasing trend. After registering a peak of 4.95 million tonnes in 1995, it reached a record low of 0.35 million tonnes in 2013 (data compiled from FAO database).

Major reasons for the declining trend in the harvests of small pelagic fish are believed to be over-exploitation of their wild stocks for direct human consumption and production of fish meal or fish oil, and climate change, particularly along the Pacific coast, which is rich in anchovy stocks (Shepherd et al. 2017). Global climate change combined with the El Niño phenomenon has escalated sea surface temperatures thereby shifting the anchovy stocks towards deeper areas making them hard to harvest (Shepherd et al. 2015). Reduced food (plankton) availability in deeper water also leads to emaciation and poor survival of the anchovy stocks (Pike and Tocher 2016). A sizeable El Niño effect was reported during 1998 and 2014, while the weaker ones were observed during 1992, 2003 and 2010 (Pike and Tocher 2016). After the strong El Niño in 2014, signs of recovery in anchovy stocks were seen in 2015 and in early 2016 thereby offering some relief on the prices of fish meal and fish oil (OECD/FAO 2016). It is projected that by 2018 the prices of fish

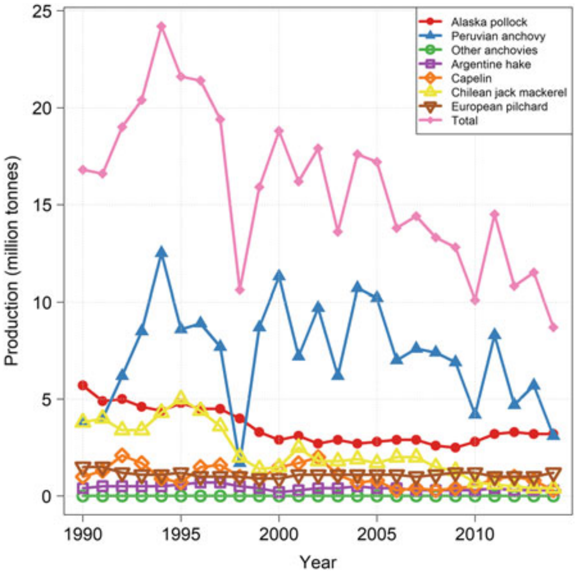


Fig. 4.7 Global pelagic fish production used for fishmeal and fish oil production (Total production includes Norway pout and Southern blue whiting in addition to the fishes mentioned in the graph). *Data Source* FAO fisheries and aquaculture data base

meal and fish oil will reach their levels of 2008, but the following decade is expected to witness a hike in their price (Fig. 4.6).

4.8 Non-aquafeed Uses of Fish Meal

Fish meal and fish oil are also consumed by livestock industries apart from aquafeed manufacturing. The global animal feed production in 2015 was 980 million tonnes contributed by poultry (45%), pig (27%), ruminant (20%), aquaculture (4%), pet (2%), and horse (1%) industries (Alltech 2015). While aquafeed accounts for only 4% of the total livestock feed production, a majority of the fish meal produced is consumed by aquaculture (68%) followed by pig (23%) and chicken (7%) feed industries. Aquafeed industry consumes 74% of the total fish oil produced and the remaining is mainly used for human consumption (22%) (Mallison 2013). The industries that process fish oil for human consumption can support higher prices than the aquafeed industry.

Of late it has been demonstrated that waste fish oil could be a raw material for production of biodiesel, which may in future result in much greater demand for fish oil globally (Behçet 2011; Lin and Li 2009). However, this demand could be offset by the prevailing lower crude oil prices and would depend on further fluctuations in their global prices to favor some interest on biodiesel production.

The static supply of fish meal from the wild harvest of small pelagic fish, combined with a rapid growth of the aquaculture industry means that alternatives to fish meal of a scale to adequately support the aquafeed manufacturing industry for a projected global production of 101 million tonnes of fish from aquaculture by 2025 must be identified and developed.

4.9 Alternative Sources of Feed Ingredients to Fish Meal

There have been a number of options available to supplement or replace fish meal as a protein source in aquafeeds. Important among them are fish processing waste and plant-based ingredients.

4.9.1 Fish Processing Waste

One of the earliest strategies for realizing sustainable aquafeeds involved the utilization of fish processing waste as raw material for the production of fish meal and fish oil. Improved per capita income and purchasing power of consumers, particularly in developing countries, have shifted the demand from whole fish to processed products like fish fillets. This generates huge amount of processing waste, which can present many environmental challenges related to their disposal. Waste

Table 4.1 Waste generation during fish processing (Arvanitoyannis and Kassaveti 2008)

Mode of processing	Fish (kg)	Solid waste (kg)
White fish filleting	1000	Skin: 40–50 Heads: 210–250 Bones: 240–340
Oily fish filleting	1000	400–450
Scaling of white fish	1000	Scales: 20–40
Deheading of white fish	1000	Head and debris: 270–320
Filleting of deheaded white fish	1000	Frames and off cuts: 200–300
Filleting of ungutted oily fish	1000	Entrails, tails, heads and frames: 400
Skinning white fish	1000	Skin: 40
Skinning oily fish	1000	Skin: 40

Table 4.2 Fish waste generated during filleting process (Waterman 1979)

Component	Average weight (%)
Head	21
Gut	7
Liver	5
Roe	4
Backbone	14
Fins and lungs	10
Skin	3
Fillet, skinned	36

Table 4.3 Proximate composition of fish waste (Esteban et al. 2007)

Nutrient	Fish waste
Crude protein (%)	57.92 ± 5.26
Fat (%)	19.10 ± 6.06
Crude fiber (%)	1.19 ± 1.21
Ash (%)	21.79 ± 3.52
Calcium (%)	5.80 ± 1.35
Phosphorous (%)	2.04 ± 0.64
Potassium (%)	0.68 ± 0.11
Sodium (%)	0.61 ± 0.08
Magnesium (%)	0.17 ± 0.04
Iron (ppm)	100 ± 42
Zinc (ppm)	62.00 ± 12
Manganese (ppm)	6 ± 7
Copper (ppm)	1 ± 1

products include fish frames, offal, trimmings and offcuts, all of which are nutritionally rich and could be used as a source of fish meal and fish oil (Ghaly et al. 2013) (Table 4.1).

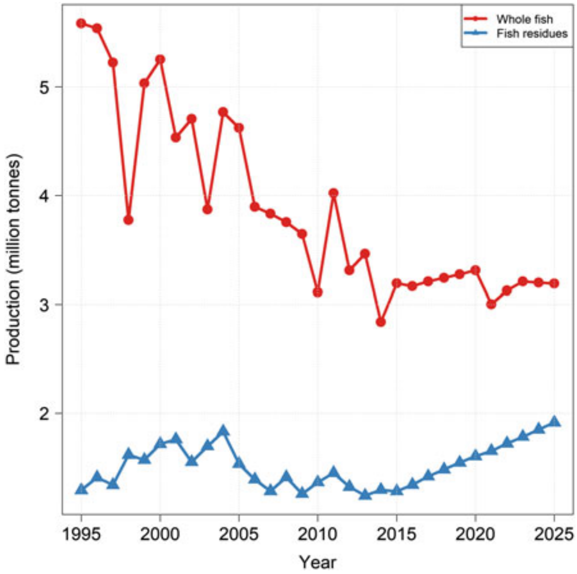


Fig. 4.8 Global fish production by resources. *Data Source* OECD/FAO (2016)

The fish processing waste generated depends on the final product prepared (Tables 4.2 and 4.3). Contribution of the fish meal produced from waste products is expected to reach 38% in the next decade (2015–2025) from the current 29% (Fig. 4.8). Even though recycling of fish products to fish meal can have a positive impact on sustainability, it may have an effect on the quality of the fish meal produced which is reported to have less protein, more ash content and an imbalanced amino acid composition compared to fish meal from capture fisheries (FAO 2016; SOFIA 2016).

Similar to fish processing waste, terrestrial animal protein meals and oils can also be used as alternatives for fish meal and fish oil. Meat by-product meals and fats reduced from the slaughtered animals like cattle, pig, sheep and poultry are some of the potential ingredients. Blood meals produced from farmed livestock can also substitute fish meal (Tacon et al. 2011). However, the inclusion levels of animal protein meals and lipids are limited by their nutrient imbalances, palatability issues, and the deficiency of certain nutrients.

4.9.2 Plant Based Ingredients—Protein Meals and Vegetable Oils

Over the past decade a major focus of the feed industry was to evaluate the inclusion of plant based ingredients as a replacement for fish meal and oil. The plant based protein meals (example: soybean meal, rapeseed meal, sunflower meal, groundnut meal, coconut meal, cotton seed meal and palm kernel meal) and

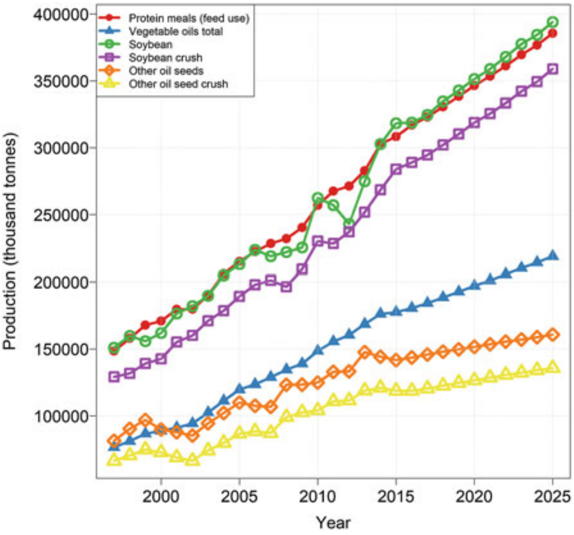


Fig. 4.9 Global oil seed and protein meal production. *Data Source* OECD/FAO (2016)

vegetable oils (soybean oil, rapeseed oil, cotton seed oil, coconut oil, palm oil, groundnut oil, sunflower oil and palm kernel oil) are increasingly included in aquafeeds to circumvent the shortage of fishmeal and fish oil.

Soybeans account for 69% of the total world production of oilseeds. Soybean production in 2015 was 318 million tonnes, of which 89% (284 million tonnes) was converted into soy crush to be further reduced as oil and protein meal (Fig. 4.9). The average annual growth rate of soybean crush production is expected to slow to 2.8% in the coming decade (2015–2025) compared to the previous decade (4.2%, 2005–2025). Soybean crush is expected to grow by 26% in volume, with an additional production of 75 million tonnes, in the next ten years.

Slow average annual growth is expected in other oilseed crush production sectors (1.7%) over the next decade compared over the previous decade (3.3%). The amount of protein meal consumed in feed production is projected to expand by 25% and reach 385 million tonnes by 2025. The production of protein meals used in feed is expected to grow at slower average annual growth rate of 2.6% during 2016–2025 compared to the period 2006–2015 (3.7%).

Vegetable oil production is projected to reach 219 million tonnes in 2025 from the current production of 178 million tonnes in 2015 with an annual growth rate of 23%. Average annual growth rate is expected to slow to 2.5% over the next decade (2016–2025) from 4% in the previous decade (2005–2015). The prices of protein meal, oilseeds and vegetable oils, which are often interdependent, are projected to be lower and stabilized in the coming decade (2015–2025) after reaching a record peak during the period from 2007 to 2014 (Fig. 4.10). Soybean price has reached a maximum of 562 US$/tonne in 2011. It is expected that the price of soybean, which is currently a major ingredient of the feed industry will stabilize around 397 US$/tonne during the next decade which is a positive sign for the feed industry.

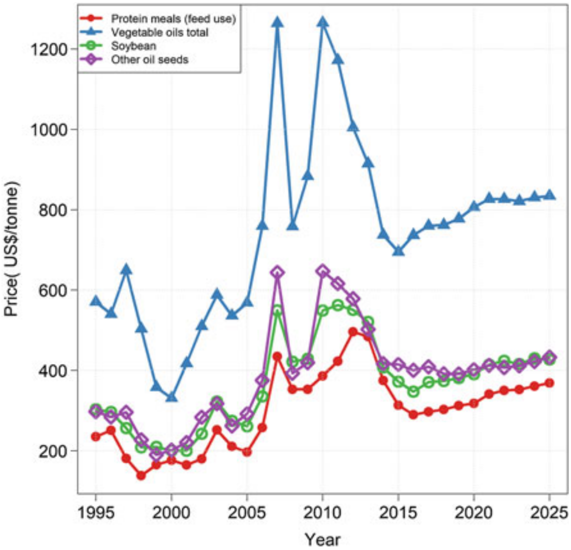


Fig. 4.10 Global oil seed and protein meal price. *Data Source* OECD/FAO (2016)

Average annual growth rate of the soybean price should fall to 1.2% in the next decade (2016–2025) compared to the previous decade's growth rate of 6.3% (2006–2015). Similarly, prices of other oilseeds should also come down during this period.

The average price of protein meal is projected to undergo a hike of 17% between the period from 2015 to 2025, and is expected to remain around 328US$/tonne during this period (Fig. 4.10). However, the average annual growth rate in protein meal price will significantly come down to 1.4% in the projected period compared to the previous 7.6% (2006–2015). Considerable reduction in the average vegetable oil price can be expected in the next decade. Average price will come down to 798 US$/tonne during 2016–2025 from the 945 US$/tonne in the last decade (2006–2015). Average annual growth rate of the vegetable oil price in the coming years is very minimal (1.8%, 2016–2025) compared to the previous decade's growth of 6.4%. The production of protein meal and vegetable oil is expected to grow in the next decade ensuring their greater availability for the feed industry. Their prices are expected to remain lower than their previous peak values making them a sustainable resource for animal feed production, particularly in aquafeeds (Fig. 4.10).

The inclusion of a wide range of plant based ingredients in aquafeed, in place of fish meal and fish oil is expected to enhance the sustainability of the industry. By reducing their utilization for manufacturing fish meal and fish oil, the low value, nutrient rich fish can be diverted for direct human consumption to boost the food, nutritional and livelihood security to alleviate the malnutrition problems, particularly in Low Income Food Deficit countries (Photo 4.6). However, major changes might be required in the preservation and transportation of such low valued fish in developing countries. This strategy is also an environmentally sustainable solution as it would also help to reduce overexploitation of fish stocks. In other words, an aquafeed industry that is less reliant on fishmeal and fish oil as a major ingredient would be more environmentally, socially and economically sustainable.

4.10 Journey to a True 'Vegetarian Fish'—The Salmon Story

The aquaculture feed industry has transformed itself over the past 15 years with a significant shift from a fishmeal based approach to formulations based on plant ingredients. One of the best examples of this change is the case of salmon feeds that are well known for their higher inclusion levels of fishmeal. While there were variations reported among different countries, the average inclusion level of fishmeal in salmon feeds was nearly 29% during the period from 1995 to 2008 (Fig. 4.11). Post 2008, there was a drastic reduction in fishmeal inclusion level observed that coincided with the surge in fishmeal price around that period and the following years. In 2015 the fishmeal inclusion level remained at 17.5% and was projected to come down further to a level of 12% by 2025 (OECD/FAO 2016; SOFIA 2016). The inclusion level of oil seed meal in salmon feed, which was as low as 3.4% in 1995 has reached 13% in 2015, and is expected to rise to 18.6% by 2025.

Another major consumer of fishmeal is the shrimp industry. Unlike in the salmon industry, the process of reduction in the levels of fishmeal inclusion in shrimp feed was gradual reaching 8.3% in 2015 from a peak of 19.3% in 1995 (Fig. 4.12). In

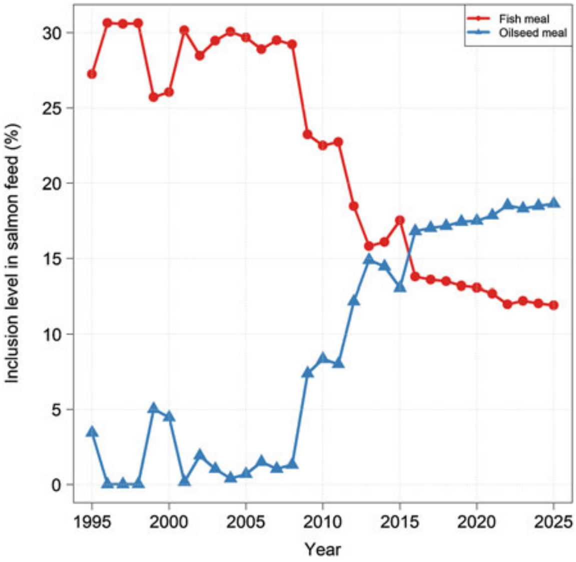


Fig. 4.11 Inclusion level of fishmeal and fish oil in Salmon feed. *Data Source* OECD/FAO (2016)

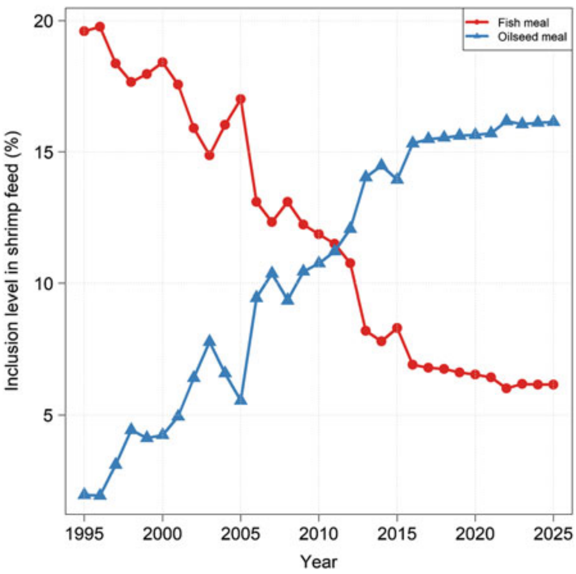


Fig. 4.12 Inclusion level of fishmeal and fish oil in Shrimp feed. *Data Source* OECD/FAO (2016)

the next decade, the inclusion level would stabilize around 6% without significant reduction any further (OECD/FAO 2016; SOFIA 2016).

'Vegetarian fish' refers to fish fed with a feed containing no animal based ingredient. This concept is gaining momentum, particularly because of the surging prices of fishmeal and fish oil, and an increasing realization of the unsustainability of the animal based ingredients in aquafeeds. The question whether vegetarian fish is an option for the sustainability of aqua feed industries is still debatable. Perhaps it is one of the feasible solutions to address the emerging concerns of sustainability in the aqua feed industry, given the fact that in future, fishmeal would be confined as a strategic ingredient in larval feeds, while a lion's share of the growout feeds for majority species would be based on ingredients derived from plants.

4.11 Challenges to a Vegetarian Feed for Fish

There are several challenges to develop a 100% vegetarian fish, particularly in the case of salmon. Presently salmon is regarded as one of the most efficient livestock in terms of edible yield, FCR, energy retention and protein retention (Bjørkli 2002). Feed Conversion Ratio (FCR) realized in the case of Atlantic salmon is 1.15 compared to the 2.63, 1.79 and 6.3 for pig, chicken and lamb, respectively. It would be difficult to maintain the present lowest FCR and higher growth rates of salmon using a 100% vegetarian feed.

Photo 4.6 Small pelagic fish (left) and shrimp (right) harvested from Lake Victoria, East Africa used as a major food resource for the local population. Photo by K.R. Salin

4.11.1 Replacement of Fish Meal by Protein Meals

The most widely used fish meal replacement in the aquafeed industry is soybean. Soybean could replace up to 33% of fishmeal as protein source in salmon diets (Carter and Hauler 2000). However, at higher inclusion levels soybean meal was found to induce a condition called non-infectious sub-acute enteritis in salmon characterized by pathological changes in the mucosal lining of the distal intestine (Baeverfjord and Krogdahl 1996). Growth performance and feed efficiency were also reported to be affected negatively by the higher inclusion levels of soybean meal. This problem could however, be solved to a certain extent by using soy protein concentrate (Drew et al. 2007; Kaushik et al. 1995; Murai et al. 1987; Olli and Krogdahi 1994). The efficacy of using soybean meal as a single ingredient replacement of fishmeal versus a combination of plant and animal based diets was also studied. It was found that the combination could result in growth comparable to diets having fishmeal as the sole source of protein (Burr et al. 2012; Davidson et al. 2016; Øverland et al. 2009; Torstensen et al. 2008). In the largemouth bass, which is a strict predator, Tidwell et al. (2005) evaluated a series of plant and animal protein sources at different rates of inclusion and fishmeal replacement. They found that poultry by-product meal could fully replace fishmeal, but that the combination of blood meal and corn gluten meal (previously identified as the best combination protein) could not.

In a study conducted on post smolt Atlantic salmon, researchers compared the growth performance of fishmeal based diet and fishmeal free diets in a recirculating aquaculture system (Davidson et al. 2016). The fishmeal free diets included mixed nut meal, poultry meal, wheat flour, and corn protein concentrate, while the fishmeal based diets contained menhaden meal, poultry meal, soy protein concentrate, and blood meal proteins. Equal growth response was achieved in both the fish meal based diet and fish meal free diets. The combination of different plant based ingredients would ensure proper balance of all essential amino acids, vitamins and minerals (Davidson et al. 2016). This is a very promising result that supports the concept of vegetarian fish and would help aquaculture to maintain its preeminent position over other livestock in terms of FCR and growth.

4.11.2 Replacement of Fish Meal and Oil by Microalgal Products

Successful reports of the replacement of fish oil by using marine microalgae, particularly *Schizochytrium* spp. have been reported in the case of salmon. In the diets for Atlantic salmon parr, fish oil was completely replaced by the *Schizochytrium* oil. There was no significant difference in growth and FCR between fish fed algae oil and those fed fish oil. The DHA content of the muscles of algae oil fed fish were higher than the muscles of fish fed with fish oil diet (Miller et al. 2007), which is promising.

In channel catfish, addition of 2% dried *Schizochytrium* resulted in higher weight gain, feed efficiency and higher level of DHA (Li et al. 2009). In grouper, it was reported that a combination of soybean meal, soyprotein concentrate and *Schizochytrium* algae meal could replace fishmeal up to 40%. *Schizochytrium* algae oil could also completely replace fish oil in grouper diets without affecting growth performance and health (García-Ortega et al. 2016). In Nile tilapia (*Oreochromis niloticus*), significantly higher weight gain, lower FCR and high protein efficiency ratio (PER) were observed in the fishes fed with 100% *Schizochytrium* algae oil compared to the fishes fed with fish oil. It was also found that fish oil replacement with algae oil resulted in better deposition of polyunsaturated fatty acids (PUFA) in the fillets of Nile tilapia (Sarker et al. 2016). In another study in longfin yellowtail *Seriola rivoliana*, 80% of the fishmeal in the feed was replaced with a combination of soybean protein concentrate, squid and algal meals without compromising growth. The diet was supplemented by amino acids methionine, lysine, and taurine. It was also demonstrated that blends of fish oil, *Schizochytrium limacinum* meal, and canola oil could be used without affecting the growth of fish (Kissinger et al. 2016).

Schizochytrium can also be used as a dietary supplement for fish or shrimp. In larval microdiets of *Litopenaeus (Penaeus) vannamei*, 4% inclusion of the *Schizochytrium* meal significantly improved their growth performance without affecting PUFA deposition in the muscles (Wang et al. 2016). This study may change our perception that dietary inclusion of fishmeal is essential for ensuring good larval survival of shrimps. While fishmeal is generally regarded as an essential ingredient in larval diets, it is now evident that fishmeal could be replaced successfully by algae meal up to a certain extent. Future research would explore partial or complete replacement of fishmeal and fish oil in larval diets.

Other algae that are used as fishmeal and oil replacement in aquafeeds include *Desmodesmus*, freeze-dried *Isochrysis*, *Chlorella* meal, *Phaeodactylum tricornutum*, *Nannochloropsis* and Spirulina. In the feeds for European seabass

Dicentrarchus labrax, it was found that 20% of protein and 36% of lipid could be replaced using the freeze-dried *Isochrysis* without affecting growth performance (Tibaldi et al. 2015). In Atlantic salmon diets, 6% of fishmeal could be replaced with *Phaeodactylum tricornutum* meal without compromising growth and FCR (Sørensen et al. 2016). In juvenile European seabass diet, a 50% fish oil replacement by *Nannochloropsis* meal was done without any negative impact on growth performance (Haas et al. 2016). Juvenile Nile tilapia fed with 30% spirulina as replacement for fishmeal was shown to improve the growth and feed utilization efficiency (Velasquez et al. 2016). In Atlantic salmon it was possible to replace 20% of fishmeal with defatted *Desmodesmus* algae (Kiron et al. 2016). In juvenile channel catfish, *Ictalurus punctatus*, inclusion of up to 40% of *Chlorella* meal with or without supplemented lysine (2%) could significantly increase feed consumption and weight gain (Kupchinsky et al. 2015).

Compared to *Schizochytrium* which was tested for complete replacement of fish oil in the diets of fish, other algae were generally used as partial replacement. Most of these studies were conducted on marine fish, particularly a few carnivores. In a study on crucian carp, *Carassius auratus* it was demonstrated that Chlorella meal could completely replace fishmeal in diets when they were supplemented with cellulases at the level of 2 g kg^{-1} (Shi et al. 2017). Camelina (*Camelina sativa*) oil is another fish oil replacement that was described to have the potential to completely replace fish oil in Atlantic salmon without affecting their growth performance and health (Hixson et al. 2014). It can be concluded that the tremendous effort invested by scientists across the world over the past decade has completely transformed the non-vegetarian fish that were fed animal based diets into partial or complete vegetarians.

4.11.3 Nutritional Quality of Vegetarian Fish Meat

One of the major concerns about the vegetarian fish is centered on its taste and nutritional quality. It is important to evaluate the nutritional quality of vegetarian fish compared to the non-vegetarian counterparts, particularly with regard to their content of long chain polyunsaturated fatty acids like EPA and DHA which are important for human health.

Nutritional quality of the salmon products collected from retailers was analyzed to determine the effect of feed ingredients on meat quality (Henriques et al. 2014). The ω-3 PUFA present in salmon fillets are mainly derived from their feed because salmon has very limited capacity for the endogenous production of ω-3 PUFA. Three types of fillets from salmon, namely farmed salmon fillets (dominant of vegetable oil markers), farmed salmon fillets (dominant of fish oil markers) and wild salmon. The farmed salmon fillets which were fed with vegetable oil had predominantly the $18{:}1n-9$ and $18{:}2n-6$ fatty acids. In contrast the fillets produced from the fish fed with fish oil rich feed had greater ω-3 PUFA, especially EPA and DHA. The farmed fish had higher total lipid content than the wild fishes.

Farmed salmon had a minimum EPA + DHA content of ≥ 1 g/100 g flesh irrespective of the lipid source. The recommended dietary intake of EPA + DHA for humans is 500 mg/day or 3.5 g/week. Consumption of cultured salmon fillet with a portion of 150 g (two meals each with 75 g of flesh in a week) is sufficient to provide the recommended ration of EPA + DHA for good cardiac health. However, wild salmon fillet tested had <0.5 g of EPA + DHA in 100 g of flesh, and so their products would have to be consumed 4–5 times in a week to ensure the recommended dietary intake (Henriques et al. 2014).

The level of inclusion of fish oil in Norwegian salmon industry was 11% in 2013. This results in 2.5 g of EPA + DHA in 100 g of salmon fillet. Two servings of salmon fillets each with 75 g in a week are sufficient to have the recommended EPA + DHA content in the diet. If the fish oil inclusion was reduced from the current 11 to 5%, correspondingly EPA + DHA in the fillet would come down to 1.3 g/100 g of fillet. It would then be necessary to consume 3.6 servings of fillet each with 75 g in a week to meet the recommended dose of EPA + DHA (Bell et al. 2001; Pike and Tocher 2016; Ytrestøyl et al. 2015). The salmon fillet is an expensive commodity compared to other fish products. Doubling the recommended dietary intake resulting from a 5% inclusion level of fish oil is obviously not economically viable.

An extensive study conducted on 3500 farmed Scottish Atlantic salmon during 2006–2015 found that an increased incorporation of fatty acids of vegetable oil origin in feed had resulted in substantially lower levels of EPA and DHA, compromising the nutritional quality of salmon (Sprague et al. 2016). By 2010 the salmon feed industry had started replacing fish oil with vegetable oil because of the increased fish oil prices. Inclusion levels of fatty acids of vegetable oil origin such as $18{:}1n-9$, $18{:}2n-6$ and $18{:}3n-3$ had increased from 15, 5 and 2 to 30, 10 and 5%, respectively in 2015. As a consequence, the EPA and DHA content had reduced by nearly 50%, a significant reduction from 2.74 g/100 g in 2006 to 1.36 g/100 g flesh in 2015 (Sprague et al. 2016). Corroborating the earlier studies, this too warranted doubling the fillet intake to meet the recommended dietary dose of fish for maintaining cardiac health.

It is interesting to note that although the EPA + DHA content in the Atlantic salmon fillets fed a predominant vegetable oil feed (100 mg/100 g) is apparently low it could still deliver a higher dose of EPA + DHA than compared to poultry meat. In broiler chicken the average EPA + DHA content was only 34 mg/100 g (Dalziel et al. 2015). Researchers are looking at alternative ways to increase EPA and DHA concentrations in vegetarian fish.

4.12 Overcoming the Challenges—The GMO Approach

One of the approaches adopted to improve the nutritional composition of vegetarian fish is the development of genetically modified (GM) organisms for incorporation in salmon feed which could induce sufficient amounts of EPA and DHA in the fish flesh. Three genetically modified organisms (GMO) were developed, namely GM Camelina (*Camelina sativa*; false flax), GM yeast (*Yarrowia lipolytica*) and metabolically engineered diatom, *Phaeodactylum tricornutum*.

Two interesting studies on the use of genetically modified Camelina as a source of EPA and DHA have been published. In the first study, researchers produced two variants of the Camelina namely RRes_EPA (that only produces EPA) in which the seeds contained EPA levels of up to 31% (mean 24%); and RRes_DHA (that could produce EPA and DHA), in which the seeds accumulated up to 12% EPA and 14% DHA (mean of 11% EPA and 8% DHA). These levels were comparable to the EPA and DHA content in fish oils. However, low levels of undesirable C18 biosynthetic intermediates were present in the GM Camelina (Ruiz-Lopez et al. 2014). In other research, comparable levels of DHA (up to 12.4%) were obtained in GM Camelina but the EPA content was very poor (maximum of 3.2%) (Petrie et al. 2014). While both these studies used the same GM plant, variation in the yield of EPA and DHA might be due to the variations in the promoters, constructs and integration sites used in the genetic engineering process (Napier et al. 2015).

Studies comparing complete replacement of fish oil with GM and wild Camelina oils have been reported. The GM Camelina oil with 20% EPA was substituted for fish oil in the Atlantic salmon feed. In comparison with the fish fed with fish oil feed and wild Camelina oil feed, the inclusion of GM Camelina oil did not affect growth performance, feed efficiency or fish health. The fatty acid profile of the salmon flesh had sufficient EPA and DHA to meet the currently recommended nutritional requirement for humans (Betancor et al. 2015). In a later study a different source of GM Camelina was used to evaluate the growth performance as well as fatty acid composition of Atlantic salmon. In this case the GM oil that had 15% of total ω-3 LC-PUFA with equal EPA and DHA profile was compared with fish oil and wild Camelina oil. The growth performance and health was optimum in GM Camelina oil fed fishes. Similar to the previous study the fatty acid composition with respect to EPA and DHA was ideal for human consumption (Betancor et al. 2016).

In a different approach GM yeast was used to produce the ω-3 fatty acids. Scientists at DuPont collected nearly 40 strains of *Yarrowia lipolytica* and screened for their performance in fermentation and ability to accumulate ω-3 fatty acids. Finally, a strain American Type Culture Collection (ATCC) #20362 was selected for further studies (Xie et al. 2015). They produced three genetically modified strains, Gen I strain Y4305 that produced EPA at more than 15% of its dry cell weight (DCW); the Gen II strain Z1978 that produced EPA at more than 20% of its DCW, and the Gen III HP strain Z5567 that produced EPA at more than 25% of its DCW (Hong et al. 2014; Xue et al. 2013). At present two commercial products are available; the New Harvest™ EPA oil, for a human nutritional supplement; and Verlasso®, farmed salmon fed with GM oil produced from the yeast (Xie et al. 2015).

The Diatom *Phaeodactylum tricornutum* has also been genetically engineered to accumulate DHA in their cells. This GM algae could be used as a replacement for fish oil in fish feeds (Hamilton et al. 2014). However, further studies are required to evaluate its potential as fish oil replacement.

Genetically modified Camelina, yeast and algae have the potential to provide feasible alternatives for fish oil for the aquaculture feed sector. Among these the GM yeast needs special mention as it could be more environmentally sustainable unlike the oil crops which are known for their negative environmental impacts like deforestation, carbon footprint, consumption of water, use of fertilizers, use of pesticides, and impacts on biodiversity. Further, the major concerns on the ethical, economic and environmental sustainability of GM products are still debated and would need a general consensus on their use in commercial aquaculture enterprises. It is therefore necessary to evaluate the various facets of their sustainability, balancing the potential harmful effects as against their benefits before any commercialization.

4.13 Concluding Remarks

Replacement of fishmeal and fish oil in aquafeed by alternative ingredients has long been a topic of research. Partial success to replace fishmeal with ingredients such as soybean meal, poultry meal and blood meals have been reported. The use of plant-based oils, microalgae, and genetically modified (GM) yeast in place of fish oil shows varying results. One of the major challenges facing replacement of fish oil is a reduced nutritional quality, particularly the lower polyunsaturated fatty acids (PUFA) content in the fish produced. The sustainability of GM crops is still a contentious issue and would need further research aimed at consumer safety and acceptability to promote their application in commercial aquaculture. Future aquafeed research priorities may also include improved techniques for mass production of algae, exploring the potential of newer ingredients, and development of precision nutrition strategies to estimate and supplement the essential micronutrients using multiple ingredient combinations of vegetarian origin for optimum survival, growth, and reproduction of fish. The recent innovations in aquafeed technology seem to have brought us closer to the production of a ‘vegetarian fish’ fed exclusively by plant-based ingredients. It is promising to note that we are striding closer to this reality.

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