2. Status of and trends in aquafeeds with special reference to Asia and western Europe

2.1 IMPACTS OF RECENT MARKET VOLATILITY ON AQUAFEEDS IN WESTERN EUROPE AND ASIA

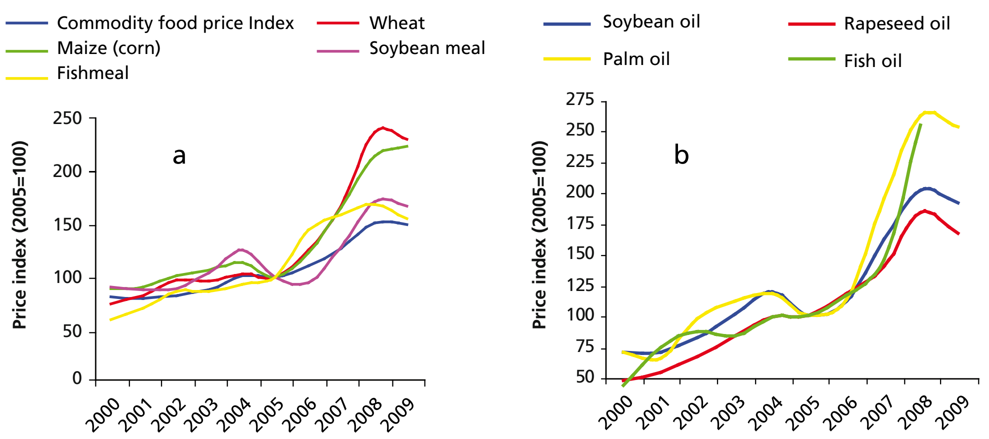
The aquafeed industry is reliant on a basket of common input ingredients such as soybean, corn, fish oil, rice and wheat for which it competes in the marketplace with other animal protein production sectors such as those raising beef, poultry and pork as well as those producing food for direct human consumption. Many of these key ingredients traditionally used in recipes for commercial and on-farm aquaculture feeds are internationally traded commodities and, therefore, aquafeed production is also subject to any global market shocks and volatility. Since 2005, the basket commodity price index (CPI) rose by about 50 percent (Figure 9). During the same period, the price of soybean meal, fishmeal, corn and wheat rose by 67, 55, 124 and 130 percent, respectively (Figure 9a). Similarly, the cost of major oils used in the feed industry increased by up to 250 percent (Figure 9b). The price of these ingredients has increased dramatically since the millennium but the rate of price increase has occurred in two phases; a steady gradual increase in prices until around 2004 followed by a dramatic exponential rise and then slight fall in the latter half of 2008 (Figure 9). The major drivers impacting on the prices of ingredients commonly used in aquafeeds are outlined below.

2.1.1 Trends in fuel costs and impacts on aquafeed production and use

The escalation in demand for commodity feed ingredients coincided with the dramatic increase in fuel prices since 2004, peaking at over US$130/barrel in July 2008 (Figure 10). Since 2005, the price index for crude oil soared to 250 percent but slipped back to around US$ 50/barrel by the end of 2008, before rising again

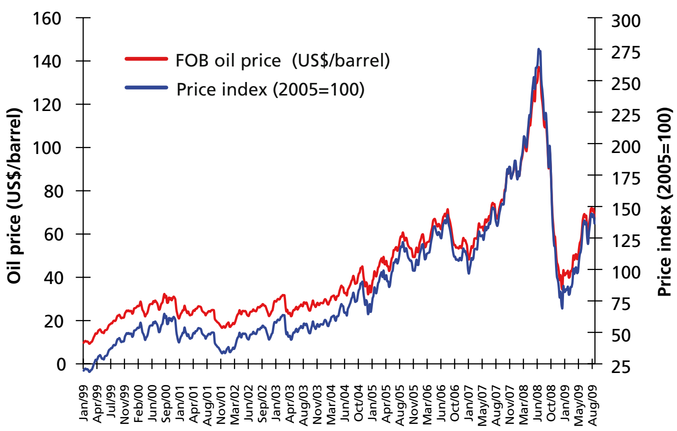
FIGURE 9

Price index (2005=100) of key (a) food commodities and grains and fishmeal and (b) plant and fish oils, used for animal feeds and human consumption



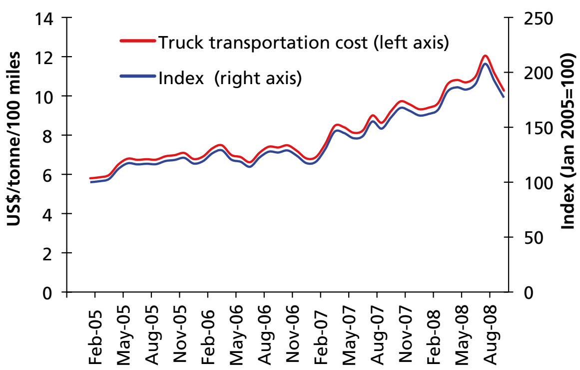
Source: Adapted from International Monetary Fund (2009).

FIGURE 10
Escalation of crude oil prices



Source: Adapted from Energy Information Administration (2009).

FIGURE 11
Monthly truck transportation cost of soybean in Brazil



Source: Adapted from USDA (2009).

to $70/barrel. This rise in fuel costs impacted heavily on transportation and production costs of those industries relying on feed ingredients and other commodities, leading to an increase in the landed cost of those ingredients. The key commodities used in aquafeed production are corn, soybean, fishmeal and oil, all of which are largely sourced from the Americas, notably Brazil, the United States of America, Chile and Argentina, and have to be shipped to major markets. In Brazil, where production areas can be over 1 000 miles from sea ports, trucks are predominantly used to transport soybean. The cost of this transportation, illustrated in Figure 11, has also escalated owing to rising fuel prices. The cost of land transportation has doubled from US$6/100 miles in January 2005 to over US$12/100 miles in July 2008 (Figure 11). Similarly, fuel prices further impacted on the landed costs of feed ingredients due to increased sea freight costs. Thus, total transportation costs increased substantially.

In Brazil, for example, the total cost for transporting 1 tonne of soybean increased by 35 percent in just two years, from US$127 in 2005 to US$171 in 2007. Rising demand and production costs increased the farm value of soybean by 42 percent. Rising oil prices impacted on the costs of fertilizers, equipment and operations. Triple super phosphate and urea prices, for example, rose from US$202 to US$909/tonne and US$223 to US$509/tonne from 2006 to 2008 (July), respectively. Overall, the landed cost of soybean from Brazil increased by 39 percent in just two years (Table 17). Trucks are predominantly used to transport soybean in Brazil. The cost of this transportation has escalated owing to rising fuel prices and is illustrated in Figure 11. Since January 2005, the cost of land transport increased by 23 percent (Figure 11).

In addition to fuel hikes, the sharp rise in sea freight was compounded by the concurrent increasing demand mainly by China for dry and container cargo ships for transportation of coal, iron ore and grain. The Baltic Exchange Dry Index, an internationally recognized measure of sea freight cost, rose from 5 000 in January 2005 to over 11 000 in July 2008.

2.1.2 Diversification of human eating habits and new uses of traditional commodities and the implications for aquafeed

The price shocks were an unusual confluence of several primary and secondary factors, which disrupted the global demand and supply balance of the commodities used for feed ingredients. The impact has been greatest since 2000. Over the last

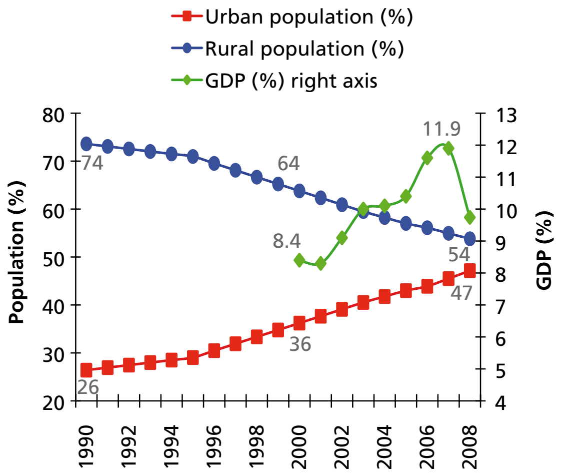
TABLE 17
Cost of transporting soybeans from Brazil (Santos) to Hamburg, Germany

	2005	2006	2007	Percent change since 2005
	US$/tonne			
Truck	79	79	98	23
Ocean	48	47	73	56
Total transportation	127	126	171	35
Farm value	164	165	234	42
Landed cost	291	291	405	39
Transport % of landed cost	44	43	43	-2

Source: USDA (2009).

decade, the strong increase in economic growth, especially in developing countries, together with the increase in population size, have raised the demand for food. While the economic growth of developed countries declined from 3.6 to 2.2 percent per year between 2000 and 2007, the economies of developing countries, especially Asian countries, grew at a staggering rate of 7 to 10 percent per year in the same period (International Monetary Fund, 2009). The increase in disposable income and prosperity was also accompanied by a notable shift in the dietary preferences of consumers in these countries as they diversified their diets to include more meat, fish and milk products, which consequently increased the demand for grains, the principal ingredient used in animal feeds. The poorer conversion ratios of feed to meat of around 2–8:1 compared with that of feed to fish of around 1–2:1 amplified the demand for the common aquafeed ingredients. Moreover, these changes occurred in the most populous countries in the world, notably in China, which had the greatest impact by skewing the global distribution of grain commodities. The impact of China, therefore, is discussed here as a special case.

FIGURE 12
Demographics and economic growth of Chinese population



Source: Adapted from National Bureau of Statistics of China (2009).

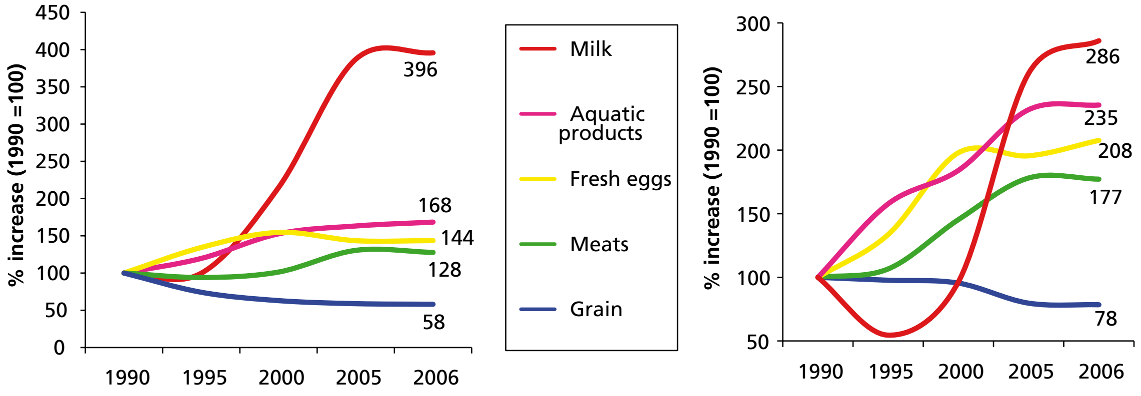
The demands placed by China on world commodity supplies used in aquafeeds were also fuelled by internal demographic and structural changes (Figure 12). Growth of the urban population averaged 4.3 percent per year from 1990 to 2006 and was expected to reach 6 percent per year by 2008. Urban population, which was 36 percent of total population in 2000, reached 44 percent in 2006 and 47 percent in 2008 (Figure 12). There was a concomitant decline in rural population by 20 percent, from 74 percent in 1990 to 54 percent in 2008 (Figure 12). These changes should be seen also in the context of differential per capita income and purchasing patterns between the rural and urban populations.

The per capita income of a person in an urban area is significantly greater than that of a person in a rural area and has risen at a significantly higher rate. Between 2000 and 2006, urban per capita annual income increased by 90 percent, from RMB6 280 to RMB11 760, compared with an increase of rural per capita annual income of 60 percent, from RMB2 253 to RMB3 600. Such an increase in affluence facilitated shifts in dietary lifestyle, with huge increases in the consumption of meat and milk products accompanied by a decline in grain consumption (Figure 13). In urban populations, consumption of milk, aquatic products, eggs and meat increased by 296, 68, 44 and 28

FIGURE 13

Increase in per capita annual purchases of major commodities in urban (left) and rural (right) households

(1990 =100. Kg values in 1990 for milk, aquatic products, eggs, meats and grain in urban area were 4.6, 7.7, 7.3, 25.2 and 131, respectively, and in rural area were 1.1, 2.1, 2.4, 12.6, 262)



Source: Adapted from National Bureau of Statistics of China (2009).

percent, respectively, from 1990 to 2006, while in the same period in rural areas increase of consumption of these same items were 186, 135, 108 and 77 percent, respectively (Figure 13). To meet this demand, animal production absorbed a significant tonnage of grains. Furthermore, the demand for oils (soybean, rapeseed and palm oil) also increased dramatically. Against this backdrop of sharply rising demand in China as well as in other populous developing economies such as India, the demand for all ingredients used in aquafeeds exerted significant upward pressure on prices. The rate of supply, however, did not keep pace with demand and key reasons for these are mentioned later.

2.1.3 The impact of climate change on the supply of aquafeed ingredients

Plant ingredients used in aquafeeds

The uncertainly concerning the availability of traditional fishmeal and fish oil and rising prices have required major industrial aquafeed manufactures to identify and evaluate alternate protein and oil sources and considerable progress has been made in recent years on substitution of fish protein and oil with proteins and oils of plant origin.

Grain crop yields, as with other arable crops, when negatively affected by variable and adverse weather conditions, increase uncertainty about grain supplies and prices. Therefore, the reliability of grain supplies for aquafeeds in the future will be influenced by short-term weather patterns and long-term predicted global warming directly through its impact on crop yields, crop pests and diseases, and soil fertility and condition. Supply will be also influenced by climate change indirectly through its impacts on economic growth, income distribution and agricultural demand (Schmidhuber and Tubiello, 2007).

During the last few years, unpredictable weather resulted in a critical shortfall of major grain and oilseed ingredients used for on-farm aquafeeds as well as for complete commercial diets. Unfavourable weather reduced crop yield and production in some countries in 2006. The crop yields in the Russian Federation and Ukraine were markedly lower due to drought. Australia encountered two years (2006 and 2007) of severe drought and South Africa also experienced drought. Consequently, the reduced world production and supply of grains and oilseeds contributed to a further decline in the global stock-to-use ratio for aggregate grains and oilseeds, and also to rising prices. In September 2006, maize prices began a significant rise to a new high.

Adverse weather patterns continued into 2007 negatively affecting yields and global grain supplies on most continents and in a great number of key countries supplying global markets with aquafeed ingredients such as rapeseed, soybean and grains. Northern Europe encountered a dry spring and floods during harvesting time, while southeast Europe suffered a drought. The droughts of 2006 in Ukraine and the Russian Federation continued into 2007. Turkey also experienced drought in 2007, which reduced yields in rain-fed production areas. In the Americas, a late heavy freeze over several consecutive days destroyed large tracts of hard red winter wheat and in the United States of America reduced yields over large areas, while in Canada, a hot and dry summer growing season resulted in lower yields for wheat, barley and rapeseed. In South America, a late freeze followed by a drought in Argentina reduced corn and barley yields (see Box 2). Droughts in northwest Africa and Australia in 2007 also affected major growing areas. The accumulative result of bad weather in 2007 resulted in the second consecutive drop in global average yields for grains and oilseeds, causing a further decline in the global stocks-to-use ratio and creating uncertainty among importers about the future availability of supplies. This placed an upward pressure on prices of plant proteins and oils used as aquafeed ingredients.

In 2009, a La Niña weather event affected crop production in the Southern Hemisphere, bringing rains to the main arable areas of Australia, serious drought to Argentine wheat production areas, reducing production by 48 percent, and sufficient rain for cereal crops in South Africa. This weather event, which was characterized by low surface-water temperatures in the Equatorial Pacific, was expected to continue well into March and April 2009. The predictably of rainfall can also affect supplies of grains. In Australia, in 2009, intermittent rain during the growing season and heavy rains during harvesting time reduced crop yields and available supplies of wheat.

It is now widely acknowledged that global weather patterns are unstable and that the frequencies of adverse climatic conditions are likely to increase. Climate change, which is being driven by global warming caused mainly by carbon emissions from industrialized countries, will continue to influence temperature and precipitation patterns around the world. This, in turn, will place severe upward pressure on water supplies in water-stressed regions of the world and may result in shifts in geophysical growing areas for the major protein crops and oil-plant crops yields of which are used in aquafeed production.

The effects of changing weather patterns are complex and several models have been developed to predict the degree of impact of such climate change on agricultural output. All models use varying assumptions (for a comprehensive review see Cline, 2007). The key assumption is that carbon concentrations in the atmosphere will increase as a result of greenhouse gas emissions from the current (2007) 365 ppm to above a threshold of around 585 ppm, reaching 735 ppm by 2080. This would foster increased production through increased photosynthetic activity, a phenomenon referred to as carbon fertilization, and hence increased yields (Cline, 2007). This positive effect, however, is reduced and reversed when the atmospheric temperature rises above 12–14°C. By combining information on carbon fertilization with information on changes in average annual temperatures and precipitations, Cline (2007) predicted the potential impact of these changes on national agricultural output.

At the regional level, assuming carbon fertilization occurs at the predicted rate, agricultural output in industrialized nations will rise by a predicted 7.7 percent, whereas that of developing countries will decline by 9 percent. Similarly, in sub-Saharan Africa (SSA), Asia and Latin America, the output is predicted to fall by 17, 7, and 13 percent, respectively. Thus, SSA and Latin America are the two developing regions most vulnerable to global warming. Countries such as Brazil and Argentina in Latin America, the United States of America and Canada, the Russian Federation, China, India, Malaysia, Indonesia and Australia are major producers and global

BOX 2

Impact of climate volatility on supplies and prices of aquafeed ingredients export and import regions

The price of grain commodities is also notably influenced by the futures trading market and forward buying of grains, a strategy to mitigate against price volatility. Such price forecasting, however, is also influenced by predictions of future yields and supplies. Another factor that is closely tracked for price forecasting is rainfall volumes and patterns, and droughts.

Due to unprecedented droughts in 2008–2009 in Brazil, Argentina and Paraguay, these countries are likely to reduce outputs and this would coincide with the recent credit crunch that forced farmers to reduce fertilizer purchases, which will likely result in reduced yields. The soybean and corn crops in Brazil and Argentina, the two largest soybean and corn exporters after the United States of America, suffered drought during critical stages of growth. According to weather station reports some areas were subjected to the worst droughts since 1971. It is estimated that in Argentina the soybean crop will be lower than last year's crop by 17 25 percent and Brazilian corn and soybean output may fall by 10 million tonnes.

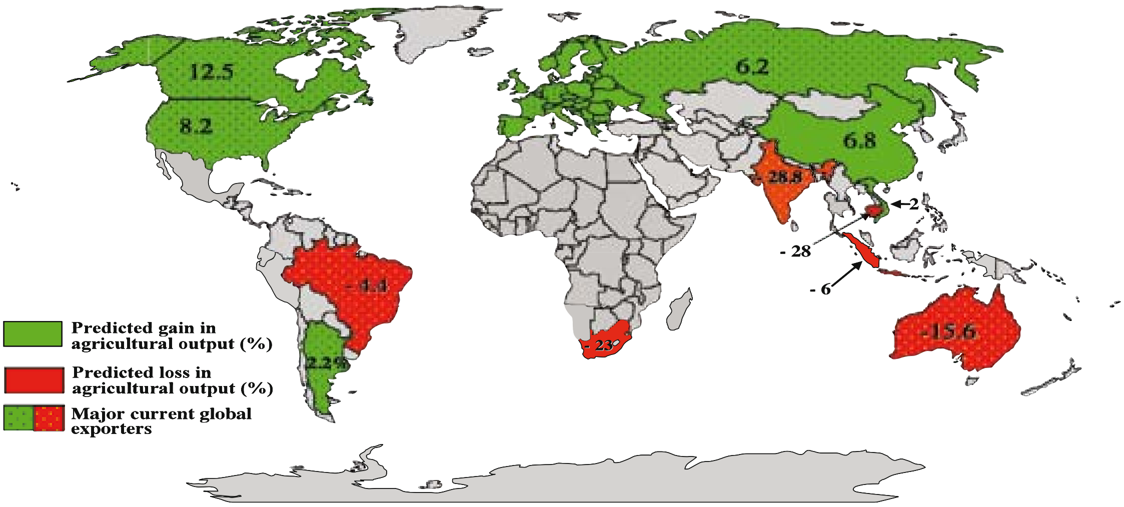
Droughts in the spring of 2009 in several parts of Europe, in particular eastern Europe, reduced outputs of wheat, putting greater reliance on imports to fulfil demands. Poor rainfall is likely to reduce EU total grain output by 4.5 million tonnes.

Reduced output of grains used in aquafeeds is also predicted for China and this is attributed to climate change. In 2006, the Government of China predicted a 37 percent reduction in corn, wheat and rice outputs in the next 20–50 years due to greenhouse effects. In 2007, the state meteorological administration predicted that China would need an additional 10 million ha by 2030 to compensate for impacts of global warming at a time when availability of farmland is diminishing due to urbanization. Rising temperatures are expected to negatively impact on rainfall amounts and distribution, and exasperate water supply as a result of increased evaporation. The evaporation rate from the currently stressed Yellow River is predicted to increase by 15 percent. In 2009, widespread drought across key soybean growing areas was also expected to reduce production by 3.2 percent.

Source: Adapted from: www.efeedlink.com

FIGURE 14

Impact of climate change on predicted agricultural output in 2080 showing main producing and exporting countries



Source: Adapted from Cline (2007).

suppliers of key protein and oils used in aquafeeds. These predicted changes, which show intraregional variation (Figure 14), show production gains for high-latitude countries and production losses for lower-latitude countries, mainly developing nations. To mitigate against such probable losses, countries can limit their losses due to climate change by switching to agricultural imports rather than growing the products imported (Cline, 2007).

Under the present scenario of global warming, the current dependency on imported aquafeed ingredients, such as soybean, maize, rice, wheat, palm oil and rapeseed, is likely to remain and will most likely increase because climate change and pressure on local land resources will reduce the probability of self-sufficiency. Moreover, because the main suppliers of soybean, maize and wheat are the United States of America, Brazil and Argentina and the main consumer markets are in Europe and Asia, these supplies will always be vulnerable to price swings due to fuel and transport price volatility (see section 2.1.1) and it is highly unlikely that prices of such commodities will reduce to pre-2000 levels for the foreseeable future.

2.1.4 Other factors affecting supplies and prices of key grain ingredients for aquafeed production

Grain production was limited due to (i) a gradual decline in acreage under grain cultivation; (ii) uncertainties about water availability for agriculture; (iii) a reduction in state research on crop yields; (iv) adverse weather conditions resulting in destruction of infrastructure for fishmeal processing plants; and (v) disease resulting in crop loss. The demand for ingredients for aquafeeds increased gradually until around 2004, and even though farm yields increased, supply could not keep pace with demand.

While the production of grains increased, although well below demand levels, the supply of fishmeal and fish oil from main producing countries such as Scandinavia, Peru and Chile into the world market diminished, putting greater upward pressure on prices of fishmeal and fish oil. Overall, the proportion of fish catch reduced for fishmeal is declining in favour of fish use for direct human consumption. In addition, lower fishing quotas for capelin, mackerel and blue whiting in Scandinavia contributed to a decline in exports from 504 000 tonnes in 2005 to 429 000 in 2008. Similarly, in South America, exports declined from 1.96 million tonnes to 1.51 million tonnes over the same period.

The price increases and availability of grain have compelled aquafeed manufactures to mitigate against these uncertainties to secure ingredients. In Europe, where aqua farming practices are predominately intensive and in Asia, where many commercially important species are farmed intensively, it is helpful to understand the structure of the commercial aquafeed industry and the sector segment it serves.

The prices were further aggravated by a series of concomitant short-term shocks. Since 2004, however, as world stocks of grains used in aquafeeds began to decline, countries like China that have huge foreign currency reserves began to import and stockpile fishmeal and other proteins and oils to secure supplies and this in turn exasperated the prices of these commodities on the world market.

In addition to high base prices on the global market, competition between the aquaculture sector and the animal husbandry sector (cattle, poultry and pigs) for key ingredients such as fishmeal caused added upward pressure on grain prices. In 2002, the aquaculture sector used 46 percent of the fishmeal on the world market, while the pigs and poultry sectors used 24 percent and 22 percent, respectively (FIN, 2007). It is expected that aquaculture will use 56 percent of the fishmeal on the world market by 2010.

2.2 TYPOLOGY OF COMPOUNDED AQUAFEED PRODUCTION IN WESTERN EUROPE AND ASIA

2.2.1 Major players of compounded aquafeed production

Profile of the aquafeed industry in Europe

Unlike in Asia, the farming of finfish in western Europe is exclusively intensive and dependent upon and driven by the use of compounded industrial feeds. Atlantic salmon, rainbow trout, seabass and seabream are the four species that dominate in European aquaculture. In 2006, production of these species totalled over a million tonnes and accounted for 81 percent of total finfish production in Europe. Moreover, salmon accounted for 54 percent (783 000 tonnes) of European finfish production. Feed manufactures, therefore, strategically monitor such developments to position themselves in geographic hotspots of production and historically around centres where key raw ingredients are produced, e.g. fishmeal and oil.

The feed industry in Europe has closely followed the market development of Atlantic salmon (and to a lesser extent rainbow trout), which is predominantly concentrated in Norway, Scotland, and to a lesser extent in the Faroe Islands and Ireland. These four northern European countries collectively accounted for 890 000 tonnes of salmonids in 2006 and over a million tonnes in 2007 (FAO, 2008b).

The aquafeed industry in Europe serving these markets is highly consolidated with three companies, Skretting, Ewos and BioMar, dominating the salmonid feed market (Table 18). In 2007, these companies manufactured over 96 percent or 1.3 million tonnes of the industrial feed used for salmon and trout production in northern Europe. In 2007, over 2.1 million tonnes of feed was used in Europe (Table 18). Details on the impact that rising prices of ingredient has had on the industry is difficult to determine because of company confidentiality. A seven and 13 percent increase in revenue for 2004 and 2006, respectively, were attributed to higher feed prices, was largely attributed to higher ingredient costs as raw materials account for 75 percent of feed production costs (Nutreco Annual Reports, 2004, 2006 and 2007; BioMar Annual Report, 2007).

TABLE 18
Key feed manufacturers and estimated industrial aquafeed production and market share

	Market share in 2007 (%)	Feed tonnage in 2006	Feed tonnage in 2007
North Europe (NE)[1]			
BioMar	23	300 000	316 250
Ewos	30	412 500	412 500
Skretting	43	500 000	591 250
Others	4	37 500	55 000
Total (tonnes)		**1 250 000**	**1 375 000**
NE (% of total)		**65**	**65**
Rest of Europe (RE)[2]			
BioMar	18	128 250	137 000
Skretting	18	128 250	130 500
Provmi	9	60 750	65 250
Persus	7	47 250	50 750
Didaq	6	40 500	43 500
Aller Aqua	5	33 750	36 250
Feedus	4	27 000	29 000
Others	33	209 250	239 250
Total (tonnes)		**675 000**	**725 000**
RE (% of total)		**35**	**35**
Total aquafeeds in NE + RE (tonnes)		**1 925 000**	**2 100 000**

[1] NE = Norway, Scotland, Ireland and Faroe Islands
[2] RE = >1000 tonnes: Denmark, Finland, France, Greece, Italy, Poland, Spain, Sweden, Germany, the Russian Federation, Turkey, Czech Republic, Croatia, Switzerland, the Netherlands

Source: Estimates extrapolated from BioMar Annual Report (2008).

Profile of the aquafeed industry in Asia

Unlike aquaculture in Europe, the species that dominate aquaculture in Asia are very diverse, with over 200 species being reportedly farmed in a range of culture systems using extensive to intensive practices. The trend in the mainstay of national aquaculture output from Asia, however, is similar to Europe and only a few species comprise reported aquaculture output at the national level (Table 19). In most major producing countries, over 70 percent of production is of just two or three species or species groups

TABLE 19

Main species that contribute at least 80% of national total aquaculture production in leading Asian countries in 2006

Country	Species/species groups[1,2]	No. species/ species groups	Contribution (%)	Main species tonnage (thousand tonnes)	National total aquaculture production (thousand tonnes)
Japan	*Japanese amberjack* (51) *Silver sea bream* (24) *Japanese eel* (7)	3	82	292.5	301.5
Myanmar	Freshwater fishes (40) Indian carps (35) *Penaeus shrimps* (10)	3	85	558	575
Bangladesh	Indian carps (49) Silver carp (19) Freshwater fishes (18) *Penaeus shrimps* (7)	3	93	866	893
Viet Nam	Freshwater fishes (47) *Pangas catfishes* (30) *Penaeus shrimps* (20)	3	97	1 466	1 512
India	Indian carps (75) Chinese carps (12) *Penaeus shrimps* (5)	3	92	3 029	3 123
Philippines	Milkfish (54) Nile tilapia (27) Other tilapias (7) *Penaeus shrimps* (7)	4	95	569	587
Thailand	*Penaeus shrimps* (48) Nile tilapia (15) Catfish, hybrid (14) Silver barb (7)	4	84	991	1 021
Taiwan Province of China	Tilapias (34) Milkfish (26) *Japanese eel* (11) *Penaeus shrimps* (5) Giant river prawn (5) *Groupers* (4)	6	85	210	217
Indonesia	Common carp (19) Milkfish (17) Nile tilapia (14) *Penaeus shrimps* (22) Torpedo-shaped catfishes (6) Freshwater fish (3)	6	81	1 254	1 293
China	Chinese carps (44) Common carp (11) Crucian carp (9) Nile tilapia (5) *Penaeus shrimps* (5) Freshwater fish (3) White amur bream (3)	7	80	21 970	22 650
Total production				**31 205.5 (97)**	**32 172.5**

[1] Values given in parenthesis are percentages of total national reported production.

[2] Species/groups in italics above are known to be farmed predominantly with commercial feeds.

Source: Adapted from FAO (2008b).

(Table 3). In 2006, around 97 percent (31 million tonnes) of production was of only a dozen species/species groups.

Mass production of these species in Asia is dependent on aquafeeds and some species are dependent almost exclusively on commercial aquafeeds and are under semi-intensive to intensive conditions. These species are highlighted in italics in Table19.

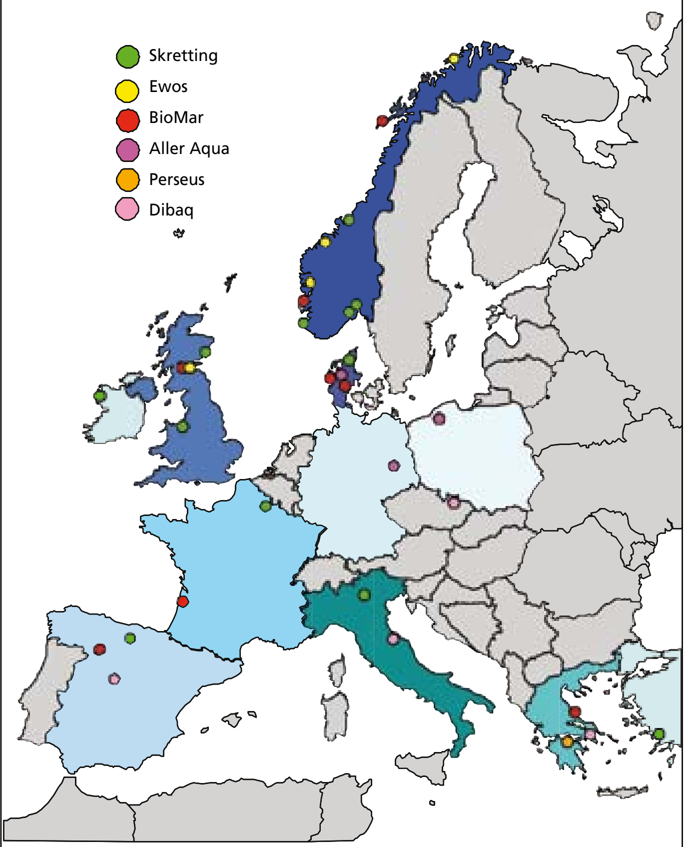
Although the current discussion about the use of animal proteins as aquafeed ingredients still largely focuses on the finite fishmeal and fish oil resources, the sustainability of aquaculture is more likely to be linked with the use of vegetable proteins and oils, and carbohydrate raw materials for aquafeeds, particularly because a significantly large proportion of production is of non-carnivorous aquatic species. In the coming years, developing countries are more likely than developed countries to be adversely impacted, if vegetable ingredients for aquaculture are not produced and sourced locally. The rising prices of key vegetable ingredients used in the aquafeeds on the international market are illustrated in Figure 9. In view of current trends, the local competition for these vegetable-based aquafeeds/ingredients will also increase as populations and disposable income in developing countries increase, as is evident in China (Figure 13) where the demand for meat and milk products, which require substantial volumes of grains to produce, continues to rise.

2.2.2 Production and distribution channels of aquafeed

Distribution of aquafeed in Europe

The major feed manufacturers are concentrated in main fish farming areas and historically near the suppliers (Norway and Denmark) of fishmeal. In Europe aquafeed needs are serviced by five main feed manufacturing companies with plants in Norway, Denmark, the United Kingdom, Ireland, Spain, France, Germany, Poland, the Czech Republic, Greece and Turkey (Figure 15). Of the three largest feed manufacturing companies, Skretting and Ewos focus on providing salmon aquafeeds for the much consolidated salmon and trout industries, while BioMar has a portfolio of aquafeeds for a more diverse number of species. These three companies account for around 90 percent of feed production in Europe.

FIGURE 15
Distribution of key aquafeed manufactures in Europe



Source: Compiled by authors.

Skretting is the largest aquafeed manufacturer, with Europe accounting for 64 percent of its global fish-feed revenue in 2008. Factories in Norway, Scotland and Ireland deliver to their respective markets. Skretting's three production plants in Norway, with a production capacity of 500 000 tonnes in 2008, mainly deliver to the Norwegian market.

Ewos, with aquafeed production plants in Norway (three plants producing 415 000 tonnes in 2008) and one plant in Scotland, is the second largest feed producer in Europe and has a European market share of around

25 percent. The markets of the four plants are highly concentrated in Scotland and Norway with feed plants delivering nationally.

BioMar group is the third largest supplier of fish feed to the European aquaculture industry, with 18 percent of the European market share, supplying 410 000 tonnes of feed in 2007 in Europe for salmon and trout in Norway and the United Kingdom and for freshwater trout (308 000 tonnes), seabass and seabream in continental Europe (102 000 tonnes). Feed factories in Norway and Scotland supply the 200 farming companies and 15 consolidated companies in Scotland, as well as Ireland and the Faroe Islands. The industry in Scotland and Norway is also highly consolidated, increasing the buying and bargaining power of these companies. Approximately 61 percent of the combined volume of the two BioMar factories in Norway and 95 percent of the volume of the one BioMar factory in the United Kingdom supply the five largest customers of BioMar (BioMar Annual Report, 2008).

BioMar has three feed production factories in continental Europe: Denmark, France and Greece. The five largest customers supplied by these three factories account for about 25 percent, 42 percent and 81 percent of volume of these factories, respectively.

BioMar's most important markets in the region are Denmark, Finland, France, Greece, Italy, Poland, Spain, Sweden and Germany. Its plants also deliver feeds to other European countries such as Bosnia and Herzegovina, Bulgaria, Estonia, Croatia, Latvia, Lithuania, Macedonia, Morocco, Romania, the Russian Federation, Switzerland, Serbia, Slovakia, Slovenia, the Czech Republic, Turkey and Austria.

Aller Aqua, which specializes in quality trout and freshwater fish feeds, has three centres of production located in Denmark, Germany and Poland, each serving specific regions in Europe. From Denmark, Aller Aqua delivers to the Russian Federation, Italy, Ireland, Sweden and Norway, while its centre in Germany supplies Germany, Turkey, Spain and Portugal. Operations in Poland focus on Poland and Eastern Europe.

Dibaq, a Spanish company, has four main production centres in Spain, Italy, the Czech Republic and Greece, each focusing on distributing to specific subregions. The centre in Spain supplies feeds to Spain, France, Portugal, Bulgaria, Romania and Morocco. The centre in Italy supplies Italy, Croatia, Serbia and Malta; the Czech Republic supplies the Czech Republic, Germany, Poland and Slovakia; the centre in Greece focuses on the home market.

2.2.3 Recent trends in the prices of compound feeds

Prices of aquafeed for indicator species in Asia and western Europe

The trends in the use of aquafeeds, both farm-made and manufactured commercial feeds, are discussed in Section 2.3. Moreover, current use of aquafeed in terms of quantities and predictions for future requirements are given in Table 20. Some feed and ingredient prices are given in Tables 21 and 22. As a result of the intensification of fish farming and the introduction of new species in aquaculture there tends to be more dependency on commercially manufactured compound feeds. Manufactured compound aquafeed prices vary from a few hundred dollars to over US$1 000/tonne depending on the species being fed. Aquafeeds for high-value and carnivorous species are in the higher price range. Farmers may be constrained from using commercial compound aquafeeds when prices of certain high-value species (see Section 1.4) fall and other freshwater fish species fetch low prices in the process of intensifying culture practices. Moreover, aquafeed prices, especially that of commercial compound aquafeeds, may increase from their current level due to increasing prices of ingredients (Table 23) and shortfalls in local supplies. This situation compels the users to import feeds. Commercial feed prices of shrimp in Indonesia increased by US$50/tonne during 2005 because of escalating prices of ingredients (Nur, 2007). Weimin and Mengqing (2007) estimated that in China there will be a shortfall of 43.2 million tonnes of cereals and 25.2 million tonnes of protein sources to meet the estimated demand of aquafeeds by

TABLE 20
Estimated aquafeed (commercial and farm-made) use in Asia during 2003–2005 and projected requirement in 2013 (million tonnes)

Country	Quantity used	Projected requirement
China	18.68	33.69
India	6.40	8.62
Indonesia	0.77	1.36
Philippines	0.59	1.49
Thailand	1.58	3.73
Viet Nam	1.50	4.00

Source: De Silva and Hasan (2007).

TABLE 21
Species-specific commercial feed prices in Asia during 2003–2005 (US$/tonne)

Species	Country				
	China	India	Thailand	Philippines	Viet Nam
Nile tilapia larvae/fry	400	–	377–450	469	–
Nile tilapia fingerlings/ growout	250–300	–		418–429	–
Grass carp	300	–	320–330	–	–
Common carp/crucian carp	250–300	–	–	–	–
Indian carps	–	90	–	–	–
Shrimp starter	850–950	978–1 067	–	931–1 022	–
Shrimp growout	450–800	844–956	–	876–967	–
Freshwater prawn juvenile	500–1 000	800–1 067	530	–	–
Freshwater prawn growout	350–600	444–800	440–520	–	–
Chinese river crab juvenile	400–500	–	–	–	–
Catfish larvae/fry	–	–	480–1 000	432	350
Catfish growout	–	–	1 333	400–407	250
Milkfish fry/starter	–	–	–	415–1 051	–
Milkfish growout	–	–	–	373–465	–
Grouper fry/starter	–	–	–	912–949	–
Grouper growout/ adult	–	–	–	849–876	–
Mud crab	–	–	–	806	–

Source: Hasan *et al.* (2007).

2015. This indicates that China will remain a net importer of ingredients to meet its aquafeed demand, contributing to high prices of ingredients on the world market. It has been reported that the feed manufacturing industry suffered from a perennial shortage of key ingredients such as fishmeal and soybean meal (AFSD–BAI, 2005). Depreciation of local currencies against the United States dollar will further increase the import cost of feed ingredients. For example, 70-90 percent of the feed cost of tilapia (US$236–309/tonne) in the Philippines in 2003 was attributed to imported feed ingredients (Sumagaysay-Chavoso, 2007). About 10 000 tonnes of fishmeal is imported into Thailand annually; there is a shortfall of soybean production of 1.68 million tonnes to meet the demands of the feed industry (Thongrod, 2007).

2.2.4 Volatility in commodity prices and underlying reasons

Fishmeal and fish oil

Fishmeal is a meal produced after cooking, pressing, drying and milling both whole fish derived from capture fisheries and food-fish trimming from fish processing plants. Fishmeal production also results in the production of fish oils. Approximately 90 percent of the fish species used to make fishmeal and oil is "presently unmarketable in large quantities as human food" (Bose *et al.*, 1991). In Europe, these species mainly include capelin, blue whiting, sandeel, sprat, herring and Norway pout and in South America, they include anchovy, jack mackerel and sardine. Because the supply of

TABLE 22
Prices of ingredients in Asia during 2003–2005 (US$/tonne)

Ingredients	India	Philippines	Viet Nam	Indonesia	Thailand	Malaysia
Animal by-products						
Fishmeal (imported)	733	855–1 000	736	710	740	661
Fishmeal (local)	466	236–536	536	545	666	500
Fish meat protein						
Shrimp meal	311	300				
Squid meal		11 212				
Fish soluble	622					
Grains						
Corn starch		409				
Sorghum	111					
Maize	133					
Broken rice	156					
Wheat flour	233	148–218	324	342	331	346
Finger millet	78					
Grain by–products						
Copra meal	144	58–236				
Sunflower meal	111					
Cotton seed cake	167					
Soybean meal	298	345–527	348	300	348	324
Rapeseed meal	144					
Rice polish	122					
Rice bran	71	55–175				
Corn bran		58				
Corn gluten meal	278					
Wheat bran	111					
Wheat gluten	1 022					
Groundnut cake	211					
Oils and fats						
Fish oil	711	509				
Cod liver oil		2 273				
Soybean oil		727				
Soy lecithin	844					
Premixes						
Vitamin and mineral		2 182–8 335				
Additives						
Phosphates		509				
Yeast	578					

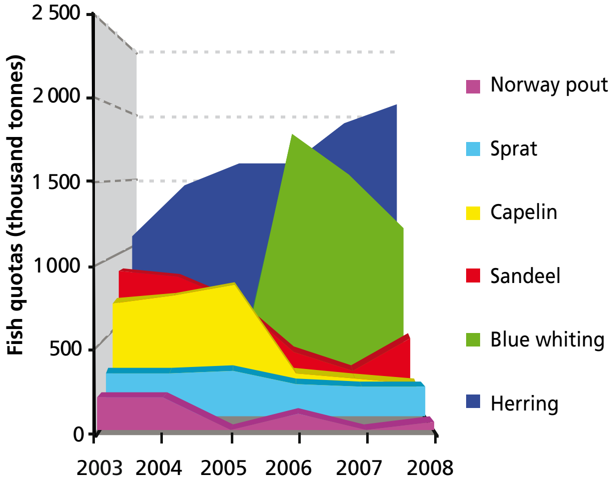
Source: Hasan *et al.* (2007).

TABLE 23
Global prices of ingredients used in aquafeeds (US$/tonne)

Nutrient source	2000	2001	2002	2003	2004	2005	2006	2007	2008
Protein									
Fishmeal	452	530	646	650	693	744	1 074	1 186	1 184
Soybean	187	181	184	215	257	206	194	264	383
Soybean meal	183	169	189	233	277	233	218	317	479
Groundnut	786	753	655	856	910	769	829	1 178	1 633
Lipid									
Soybean oil	352	347	410	500	591	496	552	780	1 220
Palm oil	261	238	357	410	435	368	417	719	948
Sunflower oil	379	436	606	650	743	1 145	713	673	1 734
Rapeseed oil						721	851	1 158	1 550
Carbohydrate									
Wheat	114	127	149	146	157	152	192	255	346
Maize	88	90	99	105	112	98	122	163	236
Rice	204	173	192	200	246	288	303	332	729

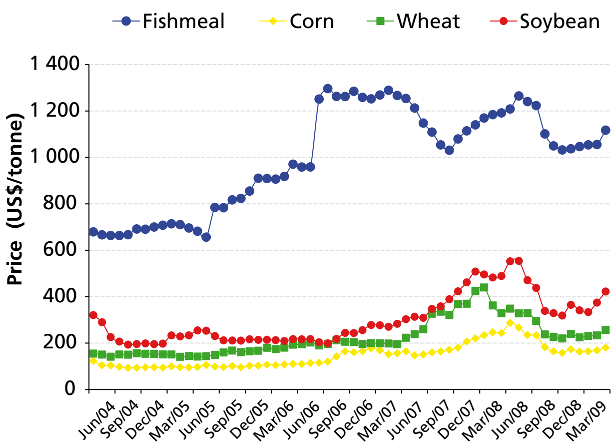
Source: Adapted from Index Mundi (2009).

FIGURE 16
Allowable quotas for fish used for reduction to fishmeal and fish oil in Europe



Source: Adapted from FIN (2008).

FIGURE 17
Commodity prices of main protein sources used in aquafeeds



Source: Data adapted form Index Mundi (2009).

fishmeal and fish oil ultimately depends on capture fisheries, their supply is primarily governed by allowable quotas for these species and is subject to seasonal variation.

Peru and Chile in South America and Norway, Iceland and Denmark in Europe are the major countries in the world where fish are used for fishmeal and oil production. Therefore, the global fishmeal supply is affected by fish landings in these countries. These landings in turn are shaped by allowable quotas and yields, particularly of fish oil, which depend on the seasons and species composition of total landings.

The decline in landings in Europe (Figure 16) and in South America have resulted in a sharp decline in fish supply. Overall, since 2003, global fishmeal supplies from the major producing countries in 2008 declined by 780 000 tonnes. This decline was sharpest in Europe. In Scandinavia, fishmeal availability declined from 504 000 tonnes in 2005 to 428 000 tonnes in 2008, while in South America fishmeal production declined from 2 million tonnes to 1.5 million tonnes in the same period. This production decline of suppliers combined with a sharp increase in imports by China led to escalating prices, which peaked at around US$1 300/tonne in mid-2006 (Figure 17).

Prices have slipped to some extent since then, but still are around the US$1 000 mark, about US$400 above 2003 prices. Currently, in 2009, prices are being checked by the global economic downturn and reduced demand for fishmeal from China, in particular.

The supply of fish oil also principally reflects the catch quotas for fish species used for reduction to fishmeal. The quantity or yield of oil recovered is influenced by seasonality and species composition used. Fish oil production also declined in line with fishmeal production but the proportional decline was greater owing to varying oil yields. Supplies in 2008 declined by around 40 percent from around 650 000 tonnes in 2004 to 399 000 tonnes in 2008.

Following record prices of nearly US$1 800/tonne in mid-June 2008, prices have sharply declined and fish oil is selling at less than half the price of US$850/tonne (Figure 18). The global economic downturn has also depressed the fish oil industry in 2008–2009. In addition, aquafeed producers are substituting more rapeseed oil for fish oil in their feed recipes, as the price of rapeseed began to fall. The high catch of mackerel in Iceland in late 2008 and the good yields of oil in the November 2008 fishing season in Peru, which increased inventories of fish oil, at a time of global economic downturn will most probably check price increase for fish oil.

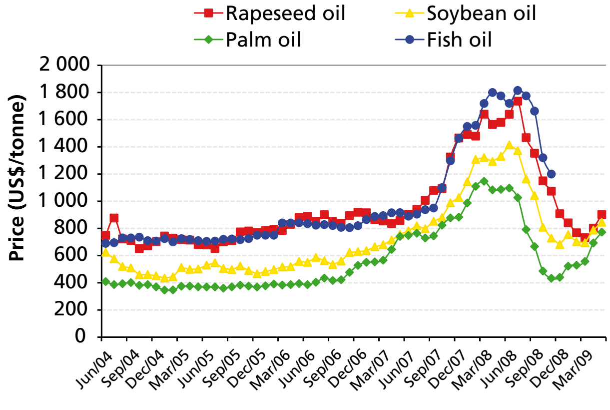
2.2.5 Alternative proteins and oils used in aquafeeds

Significant progress has been made to reduce dependency on fishmeal and fish oil through the substitution of these marine raw ingredients with proteins and oils of land origin. As was the case for fishmeal and fish oil, the price increases of vegetable protein and oil mirrored those of marine ingredients, with sharp increases recorded in 2005 for soybean, corn and wheat (Figure 17), and rapeseed, palm and soybean oils (Figure 18).

The price of corn, which has escalated from around US$100/tonne in 2004, peaked at around US$300 in June 2008 before falling to around US$180 in May 2009. The corn gluten, a protein concentrate (from the EU), used in high performance aquafeeds, however, increased from US$500/tonne in 2005 to over US$800/tonnes in November 2008. Similarly, soybean prices increased from US$200–250/tonne in 2005 and peaked at US$550 in June 2008 before declining to US$330 in March 2009. The price of protein concentrate, however, is significantly higher, escalating from around US$450/tonne in the mid-2005 to a peak of US$950/tonne in June 2008 before dropping to US$800/tonne by the end of 2008.

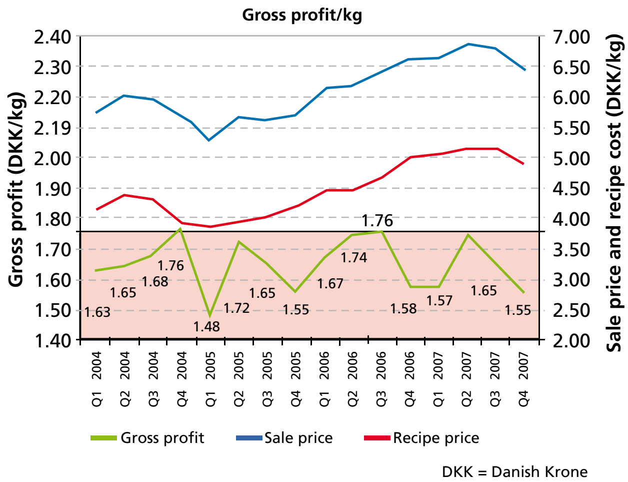
The use of oils of plant origin as a substitute for fish oil has significantly increased and the prices of these substitutes have also risen sharply (Figure 19). Prices of palm, soybean and rapeseed oil have gradually increased between 2004 and 2006, followed by a sharp increase in prices between 2007 and 2008 (Figure 18). Rapeseed oil, which is the main substitute for fish oil in Europe, for example, increased from an average of US$720/tonne in 2005 to a peak of US$1 700/tonne in July 2008. Similarly, the price of palm oil used in Asia increased from US$375/tonne in 2005 to US$1 100/tonne in June 2008. Although prices have slipped since then, resurgence in demand in 2009 is forcing prices upwards again (Figure 18).

FIGURE 18
Commodity prices of main oil sources used in aquafeeds



Source: Adapted form Index Mundi (2009).

FIGURE 19
Actual relationship between the rising cost of salmon feed production and cost of feed to farmers



DKK = Danish Krone

Source: Adapted from BioMar (2008).

Impact of commodity prices on aquafeed costs and on farmers

Rising commodity, energy and fuel costs have resulted in significant increases in the prices of manufactured and on-farm aquafeeds in Europe and Asia.

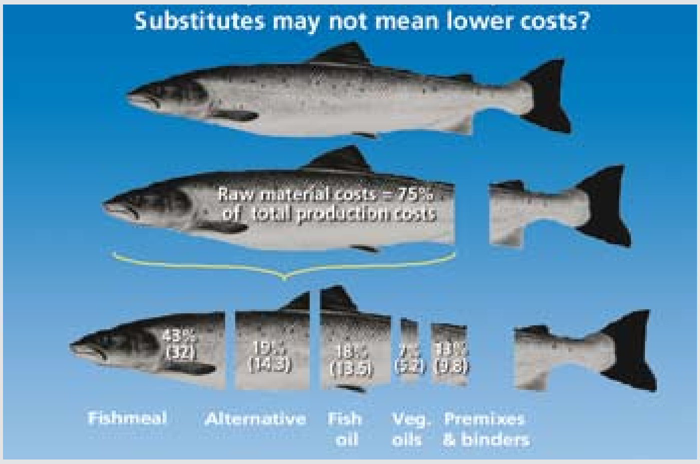
For salmon, the cost of raw materials accounts for 75 percent of production costs of formulated feeds and, therefore, the overall costs and escalation of commodity prices will have a notable impact on feed prices (see Box 3).

In Europe, BioMar, the third largest salmonid diet manufacturer, passed on increased costs to farmers to secure profit margins. Between 2005 and 2007, the kilogram recipe

BOX 3

Contribution of major groups of raw materials to production costs in 2007

Even though inclusion level of fishmeal is 25 percent, it accounts for 43 percent of raw material costs and 32 percent of total production costs. Alternative proteins (e.g. soybean, wheat and corn gluten), which can account for 45 percent of volume, accounts for 19 percent of raw material costs. The proportional costs of vegetable oils are higher than that of fish oil, while pigments/binders, which are less than 1 percent of diet, accounts for 13 percent of costs.



Source: Adapted from BioMar (2008).

costs of salmon diets increased by 25 percent (Figure 19). To secure the required gross profit margin of around 25 percent, the sale price (per kg diet) increased by a similar fraction (Figure 19). As these price increases are due to the increased price of traded commodities, such increases are likely to apply to other major feed manufacturers in Europe as well.

The higher aquafeed costs have also affected farmers in Asia. In China, since early 2006, the price of shrimp feed has increased by US$143/tonne (RMB1 000) to US$1 060/tonne (RMB7 400) after several rounds of price increases due to a large increase in the price of feed ingredients. However, considering the downturn of shrimp farming in 2008 and the limited capacity of shrimp farmers to bear further price increases, the shrimp feed price was only raised by RMB300 (US$43) per tonne. The difference between the production cost and price is borne by feed manufactures.

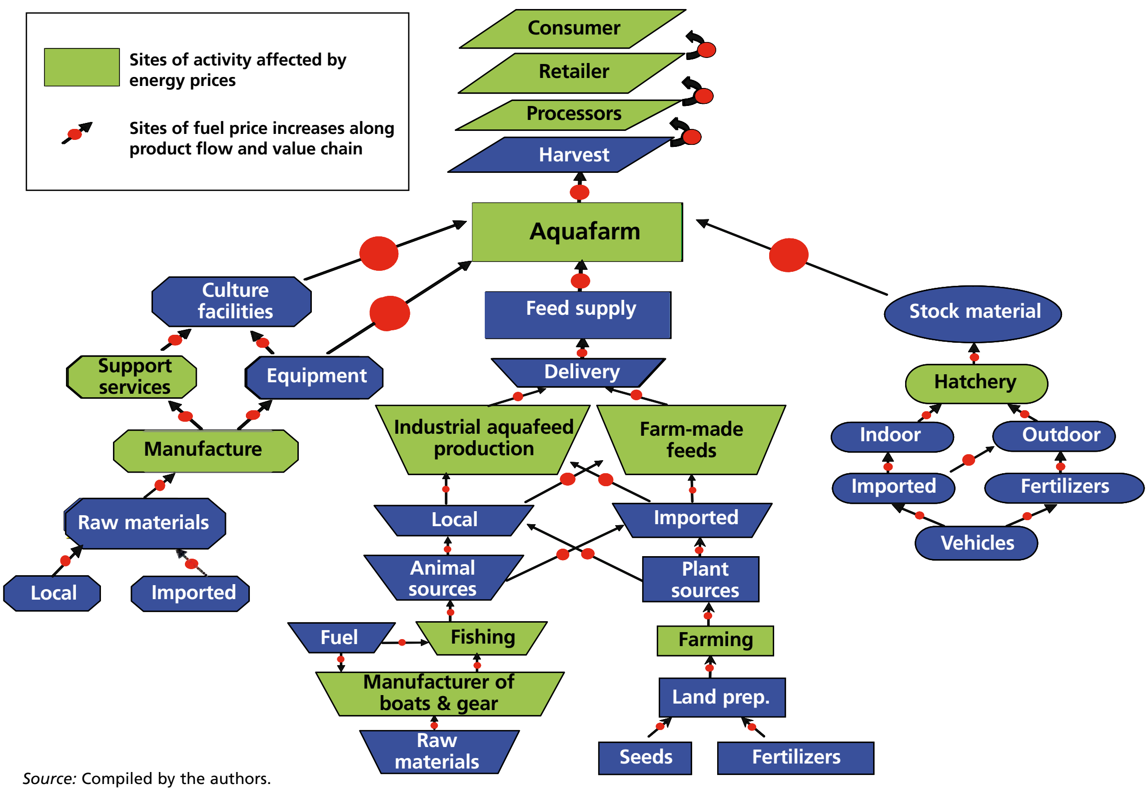
In Viet Nam, farmers and feed producers in the Mekong (Cuu Long) delta region are facing serious losses as the price of fish feed continues to rocket. In 2009, the prices of basic ingredients increased by 30 percent, raising the cost of feed by VND13 000–13 500/kg.

Rapeseed meal is a major raw material used in China as a protein substitute for fishmeal in aquafeeds and with its greater use in feeds, prices steadily increased. In 2003, prices were around RMB1 000/tonne. By April, 2009 prices almost doubled to RMB1 940/tonne.

2.2.6 Impact of rising fuel and energy costs on the cost of aquafeed ingredients

A schematic representation of the nodal points of impacts along the product chain affected by fuels price hikes is shown in Figure 20. The sharp increases in fuel prices have impacted significantly on the cost of securing the bulk ingredients used in aquafeeds and also affected the entire production chain. The high cost of fuel has impacted on fishing vessels that land fish for production and on transport of land-based

FIGURE 20
Nodal points of impact along the product chain affected by fuels price hikes



Source: Compiled by the authors.

ingredients used in aquafeeds. In addition, the higher fuel and energy costs have also reduced the profit margins of fish farmers, leading to farm closures and consolidation of the sector, especially in Europe.

In Europe, the cost of fuel for fishing vessels has escalated dramatically. According to the EU Fisheries Commissioner, Joe Borg, the price of marine diesel has shot up 240 percent across Europe since 2004 (New Europe, 2008). Further, the European Association of Fish Producers reported a 320 percent increase in fuel prices over the last five years, and a 40 percent increase in fuel prices since January 2008. Similarly, in Latin America, the cost of fuel has skyrocketed. In Mexico, where fuel accounts for 60 percent of a vessel's total operating costs, the cost of diesel fuel doubled from US$0.26 in 2006 to US$0.56 in 2008 (WW4 Report, 2008). Asian fishers, who supply a significant quantity of the trash fish used in aquafeeds, were also equally affected. In the Philippines, marine fuel prices increased by 50 percent between 2007 and 2008 from PHP40 to 60 (GMA News, 2008). In Viet Nam, the prices of diesel and kerosene went up by US$0.12 and UD$0.36 to UD$0.95 and UD$1.20, respectively (Asean Affairs, 2008), while in Indonesia, the government reduced subsidies and increased fuel prices by 29 percent overnight (Asia-Pacific News, 2008).

2.3 TYPES AND COMPOSITION OF AQUAFEEDS USED

In general, feeds and feeding practices vary according to the farming system, species under culture and stocking intensities. Traditional extensive farming systems, in which fish growth and production are dependent on consumption of natural food organisms in water, use no feed or fertilizer. In some cases, these systems use chemical fertilizers and/or organic manures, which may also be added to stimulate and enhance natural productivity of pond water. In more intensively stocked farming systems, fertilizers and supplementary or complete feeds are used.

Feeds range from single component feeds available on-farm such as grass or rice bran to farm-made formulated feeds and commercial feeds. Feeds also can be simple farm-made moist or dry aquafeeds or formulated commercially made aquafeeds. However, there is no clear definition for what is farm-made and non-farm made aquafeed and non-farm made aquafeeds. FAO suggests that farm-made feeds be defined as feeds in pellet or other forms, consisting of one or more artificial and/or natural feedstuffs, produced for the exclusive use of a particular farming activity and not for commercial sale or profit. Kitchen waste may also be considered as one of the types of farm-made aquafeed as per FAO definition as it contains one or more natural feedstuffs in non-pellet form. De Silva and Hasan (2007) suggest that mixtures of ingredients subjected to some form of processing (simple mixing, grinding and cooking) done on-farm or in small processing plants are generally regarded as farm-made aquafeeds and are often the mainstay in small-scale semi-intensive aquaculture practices. Formulated commercial feeds are composed of several ingredients, mixed in various proportions to complement each other, and form a nutritionally complete compounded diet. De Silva and Hasan (2007) categorized Asian aquafeeds into the following four groups.

(i) materials and/or ingredients of plant origin that are used singly or in combination with others (of plant or animal origin) but with little or no processing;
(ii) materials of animal origin, primarily trash fish, that are used singly or in combination with others but with little or no processing;
(iii) mixtures of ingredients that are subjected to some form of processing (simple grinding, mixing and cooking), resulting in a moist dough or in simple pellets; and
(iv) feeds that are manufactured in industrial feed milling plants and are distributed and sold using conventional market chains.

A very wide range of ingredients is used to prepare farm-made aquafeeds. They include aquatic and terrestrial plants (duckweeds, *Azolla*, water hyacinth, etc.), aquatic animals (snails, clams, etc.) and terrestrial-based live feeds (silkworm larvae, maggots, etc.), plant processing products (de-oiled cakes and meals, beans, grains and brans) and animal-processing by-products (blood and feather meal, bone meal, etc.). Vegetable ingredients are used singly or in combination with other ingredients of plant or animal origin as feeds with no or little processing in small-scale aquaculture at the lower end of semi-intensive practices, while material of animal origin such as trash fish is used singly or in combination with other ingredients with no or little processing at the upper end of semi-intensive practices (De Silva and Hasan, 2007). Usually in intensive practices, commercial complete feeds are used.

Irrespective of the feed category, the majority of the ingredients used in the feeds, particularly in categories (iii) and (iv) above, are fairly common ingredients and include fishmeal, soybean meal, various oilseed cakes (De Silva and Hasan, 2007). According to the FAO (2008b), aquaculture used 56 percent (3 million tonnes) of world fishmeal production in 2006 and 87 percent (800 000 tonnes) of fish oil production. Tacon (2008) puts this even higher, at 3.7 million tonnes of meal and 840 000 tonnes of oil. For Asia as a whole, the situation is further exacerbated as its contribution to the world supply of these three principal ingredients is minimal in comparison to the proportion that is

TABLE 24
Ingredients used commonly as sources of protein, lipids and carbohydrates

Nutrient	Ingredients used in Asia	Ingredients used in Europe
Protein	Fishmeal, soybean meal, soy protein concentrate, maize gluten, wheat gluten, sunflower, CPSP, blood meal, meat meal	Fishmeal, soybean meal, soy protein concentrate, maize gluten, wheat gluten, sunflower, CPSP, blood meal, meat meal, krill meal, gelatin, brewer's yeast
Lipid	Fish oil, vegetable oil, tallow	Fish oil, vegetable oil, tallow
Carbohydrate	Wheat meal, extruded wheat meal, wheat remillings, extruded gelatinized starch	Wheat meal, extruded wheat meal, wheat remillings, extruded gelatinized starch

Source: Compiled by the authors.

TABLE 25
Typical composition of main nutrients in feeds used in Asia (% inclusion levels)

Species	Protein			Lipid	Carbohydrate	Crude fibre
	Fry[1]	Juvenile	Adult			
Common carps	43–47	37–42	28–35	4.6–8	38.5	3–7
Crucian carp	40	30	28	5–8	36	12.2
Grass carp	25–30	28–32		4.2–4.8	36.5–42.5	12
Indian carps			20	2		15
Nile tilapia	30–56	30–40	22–32	5–12	30–40a	4–20
Grouper			50	10		2.5
Milkfish	31–35	28–31	26–29	7–8		4–7
Catfish (*Ictalurus* spp.)	35–40	30–35	28–35	5–12	40	4
Catfish (*Pangasius* spp.)			28–30	4–6		4
Shrimp	38–45	38–42	35–44	4–8	20–26	3–4
Freshwater prawn		40–45	28–35	4–9	20–35	4–6

[1] For shrimp should read as post-larvae for fry stage.

Source: Hasan *et al.* (2007).

TABLE 26
Typical composition of main nutrients in feeds used in Europe (% inclusion levels)

Species	Protein	Lipid	Carbohydrate
Atlantic salmon	35–55	30–40	7–15
Rainbow trout	42–45	20–24	
Gilthead seabream	45–50	12–24	20
European seabass	43–50	12–25	20
Turbot	48–52	12	
European eel	40–49	12–16	20
Sea trout	52	12	17
Common carp	30–35	5–10	30–40

Source: Adapted from Aquamax (2008).

TABLE 27
Ingredients and their composition (% inclusion) in manufactured feeds in Asia

	Species									
	Nile tilapia		Grass carp	Common and crucian carp	Shrimp		Freshwater prawn		Milkfish	Grouper and Asian seabass
	Fry	Fingerling/ growout	Fingerling/ growout	Fingerling/ growout	Starter	Growout	Juvenile	Growout		
Animal by-products										
Fishmeal	50	4–12	4	3–6	30	23–25	23.3–33.8	11.3–22.5	11	20
Shrimp meal										10
Shrimp bran						1				
Shell meal							1–3.2	1.6–4.8		
Poultry by-product meal	2									
Hydrolysed protein	4									
Blood meal										8
Bone meal					1.1					20
Squid meal					3	2				1
Grains										
Corn		22.1–6.2	8.95–12.95	6.9–10						
Wheat flour			16.8–18.8	11.85			14.35–19.25	14.5–18.5		
Bread flour									5	
Rapeseed										
Grain by-products										
Soybean meal	17	34–46							30.8	6
Soybean cake			5–14	27–32	15	15	29.4–32	21–23.2		
Rapeseed meal										
Rapeseed cake			41–51	40–41			15.2–16	21.6–26		
Rice bran									49.2	7
Corn gluten meal	12									
Wheat bran			10–11	4				6.95–10		
Wheat meal	4.2				29.5	28.6–30.6				
Wheat middling	4	30								
Groundnut cake					11	16				

TABLE 27 – (CONTINUED)

	Species									
	Nile tilapia		Grass carp	Common and crucian carp	Shrimp		Freshwater prawn		Milkfish	Grouper and Asian Seabass
	Fry	Fingerling/ Growout	Fingerling/ Growout	Fingerling/ Growout	Starter	Growout	Juvenile	Growout		
Oils and fats										
Fish oil	1				1	1				
Cod liver oil									2	6
Soy oil									2	
Vegetable oil		0.5–3.6								
Premixes										
Vitamin				1			1	1		4
Mineral			1							3
Vitamin and mineral	0.5	0.5								
Additives										
Phosphates		1.4–2.6			3.5	3.5–4.5				
Growth and immune enhancements			1.25	1.25	1	1	1.25	1.25		
Molt-inducing agent							0.2	0.2		
Lure agent					0.1	0.1				
Polysaccharide					0.1	0.1				
High stability vitamin C					0.1	0.1				
Sea salt					1.5	1.5				
Yeast					3	3				
Binder		0.01	1	1	1.2	1.2	1.2	1–1.2		

Source: Hasan *et al.* (2007).

TABLE 28
Ingredients and their composition (% inclusion) in manufactured feed in Europe

Ingredients	Reference	
	Waagbø *et al.* (2001)[1]	Skretting (2008)[1]
	35	30
Fish oil	28	18
Fish ensilage	5	4
Corn and wheat gluten	7	
Vegetable protein		25
Soy products	6	
Soybean oil	3	
Vegetable oil		11
Wheat	12	
Wheat meal		10
Other	4	2

[1] Cited in Aqua Web (2009).

used by the regional animal feed industry (De Silva and Hasan, 2007). For example, while Asia produces only 17 percent of the global fishmeal supply, it consumes 47 percent of it.

Ingredients commonly used as nutrient sources are given in Table 24. Species-specific composition of main nutrients used in formulated commercial fish feeds in Asia and in Europe are given in Tables 25 and 26. In terms of ingredients used in commercial aquafeeds, Asia and Europe do not differ much (Tables 27 and 28). Irrespective of the region, the commercial aquafeeds largely depend on soybean products and corn or wheat products. Additives are mainly used in high-value shrimp aquaculture in Asia.

Apart from materials of animal and plant origin used as ingredients in aquafeeds, trash fish still remains the traditional feed for high-value marine carnivorous fish throughout the Asia-Pacific region and is likely to remain so for some time. They are currently an indispensable feed for carnivorous fish and are also used in farm-made feeds for omnivorous species in some countries such as China, Viet Nam and Indonesia. It has been estimated that Viet Nam uses nearly 900 000 tonnes of trash fish and China will require approximately 4 million tonnes of trash fish by 2013 to sustain marine cage culture activities (De Silva and Hasan, 2007). However, the depleting availability of trash fish is considered one of the most serious constraints for aquaculture development in Viet Nam. The supply of trash fish in Asia is highly seasonal and dwindling (Edwards, Tuan and Allan, 2004). Their efficacy as an aquafeed is debateable and their preferred use appears in many instances to be based more on farmer perceptions than economic reality (De Silva and Hasan, 2007). Moreover, the fishmeal manufactured mainly from trash fish, spoiled fish and processing waste is inferior in quality and often contains high levels of histamine and cadaverine substances (Hung and Huy, 2007). Dependency on trash fish may continue with the expansion of marine cage aquaculture despite the socio-economic and environmental consequences of using trash fish and feed. However, because of the negative consequences for sustainability of the use of trash fish in terms of: (i) the impact on near-shore fishery stocks; (ii) damage to the coastal environment; (iii) their potential to introduce disease in the cultured fish; (iv) inconsistent and inferior quality; and (v) depleting availability, the growth of high-value marine carnivores will have to depend on commercial complete feeds sooner rather than later.

2.4 POSITIONING OF THE INDUSTRY TO MEET THE CHALLENGE OF SECURING AQUAFEED TO SUSTAIN AQUACULTURE

2.4.1 Search for substitution of fishmeal and fish oil due to rising prices and availability

Fishmeal and fish oil are highly favoured ingredients in aquafeeds for a number of reasons, including:

- high protein, essential amino acids, mineral and essential fatty acids;
- high palatability and digestibility, thus increased growth of fish and less feed wastage; and
- health benefits such as improved immunity, survival rate and reduced incidences of deformities.

Fishmeal production is constrained by its dependency on a finite resource, viz, pelagic fish, the stocks of which are declining due to the cyclic El Niño effect, and the likely continuation of high prices. Landings of small pelagic fish for fishmeal production in South America, which produces around 40 percent of the world's fishmeal and fish oil, were very low in the first quarter of 2007, some 20 percent below the previous year and around 14 percent below the five-year average (Globefish, 2007). Apart from high prices, the aquaculture industry is in competition for fishmeal, because fishmeal is used for animal production and is a primary protein source in the diets of cattle, poultry and pigs. In real terms, world poultry and pig meat production increased from 76 million tonnes and 96 million tonnes in 2003, respectively, (FAO, 2004) to 83.7 million tonnes and 106.9 million tonnes in 2006, respectively, (FAO, 2007). Although current annual growth of poultry and pig meat production is not as high as that in aquaculture, higher protein percentages (15 percent to 20 percent) are used and absolute production levels in poultry and pig meat industries, lack of fishmeal availability may be of serious concern for fish-feed development. For Asia as a whole, the situation is further exacerbated as its contribution to the world supply of these principal ingredients is minimal in comparison with the proportion that is used by the regional animal feed industry (De Silva and Hasan, 2007). For example, while Asia produces only 17 percent, it consumes 47 percent of the global fishmeal supply.

A closer look at how the trade-offs are likely to take place in future between the main types of aquaculture will provide a clear insight into the danger of dependency on fishmeal for fish feeds. Within the aquaculture sector, the main consumers of fishmeal are shrimp (22.8 percent), marine fish (20.1 percent), salmonids (19.5 percent) and carps (14.9 percent) (Tacon, 2005). Increase in fishmeal and fish oil production to meet the demand of the aquaculture and livestock industries is very unlikely as the landings of the capture fisheries of forage fish, which are reduced to fishmeal and fish oil, are on the decline. Because the emphasis is on the high-value marine species and intensification of carp culture, dependency on fishmeal will be risky and the competition between livestock producers and aquaculturists could be more severe if an alternate to fishmeal is not found. Moreover, if aquaculture sustains its current growth rate, potentially all fishmeal and fish oil would be utilized by 2020 and 2010, respectively (Tacon, 2005), and finding suitable alternatives to fishmeal and fish oil that are sustainable, as well as improving feeding practices, would be a practical solution.

In the search for viable alternative feedstuffs to fishmeal for aquafeeds, candidate ingredients must possess certain characteristics, including wide availability, competitive price, as well as ease of handling, shipping, storage and use in feed production (Gatlin *et al*., 2007). The main challenge in replacing fishmeal and fish oil is to find alternatives that maintain acceptable growth rates, animal health and changes to the final product

TABLE 29
Alternate protein sources used in fish feeds

Alternative	Species	Inclusion level[1]	Limitation	Reference
Soybean meal	Atlantic salmon	34% (40% FM replacement)	Poor digestibility	Refstie, Storebakken and Roem (1998)
	Rainbow trout	42% (50% FM replacement)	Methionine 0.3%	Kaushik *et al.* (1995)
	Gilthead seabream	39.5% (47% FM replacement)	Poor amino acid profile	Martínez-Llorens *et al.* (2008)
	European seabass	25% (27%FM replacement) -50% (50% FM replacement)	Poor digestibility	Tibaldi *et al.* (2006)
	Nile tilapia	43–47% (100% FM replacement) (extruded soybean meal/extruded full-fat soybean)	DL methionine 0.5%, L-lysine 0.5%	Goda *et al.* (2007b)
	Milkfish	(67% FM replacement)	Methionine	Shiau *et al.* (1988)
	Carp	(100% FM replacement)	Methionine, lysine and oil	Viola *et al.* (1982)
	Catfish	61% (75% FM replacement)	Methionine	Fagbenro and Davies (2001)
Soy protein concentrate	Atlantic salmon	50% (75% dietary CP)	Methionine 0.3%	Storebakken, Shearer and Roem (2000)
	Rainbow trout	62% (100% dietary CP)	Low in methionine (methionine 0.4%)	Kaushik *et al.* (1995)
	Gilthead seabream	20% (30% FM replacement)	Poor palatability	Kissil *et al.* (2000)
	Nile tilapia	100%		Abdelghany (1997)
Pea seed meal	European seabass	40% (12% FM replacement)	Poorly digestible content	Gouveia and Davies (1998)
	Milkfish	26% (20% FM replacement)	Reduced nutrient and energy digestibility and energy utilization efficiency	Borlongan, Eustechio and Welsh (2003)
	Catfish	33%		Davies and Gouveia (2008)
Pea protein concentrate	Atlantic Salmon	27% (33% FM replacement)		Carter and Hauler (2000)
	European seabass	36% (60% FM replacement)	Poor palatability, low methionine	Tibaldi *et al.* (2005)
	Nile tilapia	14.8% (30% FM replacement)	Poor amino acid profile	Schultz *et al.* (2007)
	Catfish	30.8%		Davies and Gouveia (2008)
Canola meal/ concentrate	Atlantic salmon	35%	Presence of glucosinolates/phytic acid	Sajjad and Carter (2004)
	Rainbow trout	< 25% (100% FM Replacement)	Poor palatability and low amino acid	Carter and Hauler (2000)
Cotton seed cake	Nile tilapia	100		El-Sayed (1990)

TABLE 29 – CONTINUED

Alternative	Species	Inclusion level[1]	Limitation	Reference
Lupin concentrate	Atlantic salmon	22% (33% FM replacement)	Poor palatability & digestibility	Carter and Hauler (2000)
Corn gluten	Atlantic salmon	50% (60% FM replacement)	Low lysine content	Mente *et al.* (2003)
	Rainbow trout	23.41 (40% FM replacement)	Poorly digestible carbohydrate fraction	Morales *et al.* (1994)
	Gilthead seabream	40% (60% FM replacement)	Low arginine and lysine content	Pereira and Oliva-Teles (2003)
	Nile tilapia	≤ 30% (100% dietary CP)	Poor arginine, histidine and threonine content	Goda *et al.* (2007b)
Wheat gluten	Atlantic salmon	16.7% (36% FM replacement)	Lysine	Storebakken, Shearer and Roem (2000)
Rapeseed protein concentrate	Gilthead seabream	42.5% (60% FM replacement)	Poor palatability	Kissil *et al.* (2000)
Sunflower	Atlantic salmon	27% (33% FM replacement)	(DL methionine) and presence of hulls	Gill *et al.* (2006)
	Rainbow trout	42% (40% FM replacement)		Sanz *et al.* (1994)
	Gilthead seabream	12% (9% FM replacement)	High fibre content	Lozano *et al.* (2007)
Faba bean	Nile tilapia	24%(20% replacement of dehulled soybean meal)	Poor methionine content, high phenolics and tannins content	Azaza *et al.* (2009)
Animal by-products				
Meat and Bone meal	Gilthead seabream	28% (40% FM replacement)	Histological liver alterations, reduced protein and lipid digestibility	Robaina *et al.* (1997)
Poultry by-product meal	Gilthead seabream	71% (100% FM replacement)		Nengas, Alexis and Davies (1999)
	Nile tilapia	30% (66% FM replacement)		Fasakin, Serwata and Davies (2005)
	Catfish	27% (40% FM replacement)	Poor nutrient availability and amino acid imbalance	Abdel-Warith, Davies and Russell (2001)
Blood meal	Rainbow trout	22.7%		Luzier, Summerfelt and Ketola (1995)
	Gilthead seabream	5% (15% FM replacement)	Low dietary methionine content and low digestibility	Martínez-Llorens (2008)
	hybrid tilapia	< 21.7% (66% FM replacement	Amino acid imbalance and poor digestibility	Fasakin Serwata and Davies (2005)
Poultry by product meal	Rainbow trout	20 (40% FM replacement)		Mustafa and Huseyin (2003)
	African catfish	17%–34.5% (100% FM replacement)	Poor palatability, low nutrient availability and amino acid imbalance	Abdel-Warith, Davies and Russell (2001); Goda, El Haroun and Chowdhury (2007a)
	Chinook salmon	20%	Poor palatability	Fowler (1991)
Feather meal	Rainbow trout	15%	Deficiency in lysine or other amino acids	Bureau *et al.* (2000)
	Rainbow trout	15%		Fowler (1990)
	Rainbow trout	30%	Low lysine content	Pfeffer, Wiesmann and Heinrichfreise (1994)
	Nile tilapia	9.9% (66% FM replacement)	Poor amino acid profile	Bishop, Angus and Watts (1995)
Krill meal	Rainbow trout	8.9% (15% FM replacement)	Fluoride accumulation in vertebral bones	Yoshitomi *et al.* (2006)

[1] FM = Fishmeal

Source: see the references in the table.

TABLE 30
Advantages and disadvantages of some of the plant substitutes for fishmeal

Plant substitute	Advantages	Disadvantages
Soybean meal (SBM)	Economical and nutritious with high crude protein (44–48%) Cystine in higher concentration	Concentrations of the 10 essential amino acids (EAA) (lysine, methionine, cystine and threonine may be limiting) and tyrosine are lower; crude fat and ash content is lower but can be overcome with supplementation; high in non–starch polysaccharides; reduced feed intake; growth and development of intestinal enteritis; presence of anti–nutritional factors such as lectin; low in available phosphorous
Soybean protein concentrate (SPC)	EAA concentration matches or more to EAA concentrations in fishmeal	Methionine, cystine may be limiting; not economical for large scale use; crude fat and ash content is lower but can be overcome with supplementation
Soy protein isolate (SPI)	EAA concentration matches or more to EAA concentrations in fishmeal	Methionine, cystine may be limiting; not economical for large-scale use; crude fat and ash content is lower but can be overcome with supplementation
Canola meal	Not widely used in aquafeeds, similar to the protein content of SBM	The price similar to that of SBM; low in available phosphorous
Canola protein concentrate	Protein content similar to high-quality fish fishmeal, widely tested as a protein source for salmonids and other carnivorous species of farmed fish, supports growth rates similar to those of fish fed fishmeal-based diets	Amino acid supplements needed to overcome limiting amino acid levels; feeding stimulants are needed to overcome reduced feed intake
Corn gluten meal	Crude protein content of 60–73%; corn gluten meal is currently widely used in aquafeeds for salmon and several marine species such as European seabass and gilthead seabream; highly digestible	Limited in commercial production; deficient in EAA lysine
Corn distillers dried grains with solubles (DDGS)	28–32% crude protein	High in fibre content
Cottonseed meal	10 and 30% of solvent extracted; 40% protein CSM can be used in aquaculture diets without growth depression	Presence of gossypol may have toxic effects
Peas/lupins	High protein apparent digestibility coefficient	Lysine and methionine are limited; high levels of carbohydrate (fish do not metabolize non–starch polysaccharides in lupins); presence of anti–nutrient quinolizidine alkaloids; lysine is limiting
Wheat	Low in protein (<11)	Wheat is primarily an energy source based on its high starch composition (typically >70%); lysine is limiting
Barley	Barley protein is well digested	Low crude protein content (9–15%); high in fibre; low in available phosphorous; lysine and arginine may be limiting; high in fibre

Source: Gatlin *et al.* (2007).

TABLE 31
Advantages and disadvantages of some of the animal by-product substitutes for fishmeal

Animal by-product substitute	Advantages	Disadvantages	Reference
Hydrolysed feather meal (HFM) (either steam or enzyme treated)	Proposed optimum replacement rates of fishmeal by enzyme treated HFM are; European seabass ≤5%, turbot ≤5%, gilthead seabream 5%, red tilapia <66%, rainbow trout <20%	Steam treated is less digestible compared with enzyme treated; deficient in lysine and methionine	Laporte *et al.* (2007)
Poultry by-product meal (PBM)	Typically contain 66% CP, 13% CF and 10-18% ash. Proposed optimum replacement rates of fishmeal by PBM are: European seabass 25%, turbot 10%, gilthead sea bream 25%, red tilapia 66%, rainbow trout 15%	Deficient in lysine, methionine and histidine	Laporte *et al.* (2009)
Blood meal	Rich in lysine	Deficient in methionine; highly sensitive to heat damage and drying conditions with profound effect on protein digestibility	Bureau (2008)
Fish by-products from fish processing plants	Regarded as the best nutritional substitutes for fishmeal and fish oil due to their nutritional characteristics	Issues related to potential pathogens and contaminant harmful to both fish and consumers need to be addressed through proper treatment	Hardy (2004)

Source: see the references in the table.

(Tacon, Hasan and Subasinghe, 2006). Further, they must possess certain nutritional characteristics, such as low levels of fibre, starch, especially non-soluble carbohydrates, and anti-nutrients, and have relatively high protein content, favourable amino acid profile, high nutrient digestibility, and reasonable palatability (Gatlin *et al.*, 2007).

There is an increasing trend towards replacing fishmeal with alternate protein sources, particularly plant material (Table 29), which are believed to be in abundance at a reasonable price when compared with fishmeal, which is costly due to the dwindling supply and erratic price.

The plant materials and animal by-products used in fish feeds as substitutes for fishmeal, and their advantages and disadvantages are summarized in Tables 30 and 31.

2.5 RESEARCH AIMED AT SUSTAINABLE SUPPLIES OF AQUAFEEDS

Solutions to fishmeal inclusion in aquafeeds are multi-faceted. Apart from inclusion of plant protein sources (from more plant species) and animal by-products, other initiatives included: (a) pre-processing techniques of plant material to reduce the effects of anti-nutritional factors in order to enhance nutritional value; (b) breeding of plants with a better amino acid profile and less antinutritional factors; (c) selecting fish species with lower marine protein requirements (e.g. herbivores); (d) converting low grade land animal by-products into high-value protein, and e) most recently, the use of new innovative protein sources.

The excessive reliance of aquaculture on fishmeal and fish oil has already led to dedicated research such as RAFOA (Research on Alternatives to Fish Oil in Aquaculture, coordinated by the University of Stirling, Scotland) and PEPPA (Perspectives of Plant Protein Use in Aquaculture, coordinated by INRA, France) under the fifth framework of the EU. The targeted reduction of dependency on fishmeal and oil by this research is given in Table 32.

It has been established that blends of vegetable oils can replace fish oil for the major part of the growth period in several farmed fish (Atlantic salmon, rainbow trout, European seabass and gilthead seabream) (Aquamax, 2008). This has been achieved by blending vegetable oil to mimic the levels of total saturated, total monounsaturated and total polyunsaturated fatty acids in fish oils, and their high levels of omega-3 polyunsaturates, except that of the C18 linolenic acid (18:3w3).

Biological enhancement through micro-organisms such as yeast and bacterial and fungal fermentations have been investigated to determine their capacity to reduce the effects of anti-nutrients in plant materials and current results demonstrate great potential of this method for removing anti-nutrients and adding essential nutrients such as protein and amino acids (Mukhopadhyay and Ray, 1999; Bairagi *et al.*, 2004). The overall goal of these processes is to increase protein concentration and decrease the levels of anti-nutrients (Gatlin *et al.*, 2007). The knowledge on genetic manipulations to achieve better traits such as protein and oil content of plants has been extended to lower the anti-nutritional factors. Genetic manipulations have been investigated to achieve low levels of phytic acid and thereby enhance available phosphorous (Guttieri *et al.*, 2004), increase essential amino acids such as lysine (Gibbon and Larkins 2005; Stepansky *et al.*, 2004), increase the levels of oil (Laurie *et al.*, 2004) and increase micronutrients such as antioxidatives (Capell and Christou, 2004).

TABLE 32
Targeted reduction of dependency on fishmeal and oil

Species	Current inclusion (%)		Targeted inclusion (%)	
	Fishmeal	Fish oil	Fishmeal	Fish oil
Atlantic salmon	35–47	25–33	12–16	8–12
Rainbow trout	30–35	20–25	5	5
Seabream	40–45	15–20	15	10
Common carp	20–25	5–10	0	0

Source: RAFOA and PEPPA (personal communication).

Innovative new protein sources are mainly focused on microbial and algal species. However, cost of production will be an issue with most of the manufacturers of microbial proteins (Aquaculture Innovation, 2008). Locating the microbial protein manufacturing facilities very close to the major feed manufacturing locations may be a measure to keep the cost down by minimizing transport costs, which tend to increase over time. A company in Asia is developing microbial product at present with considerable interest from Asia's largest integrated feed company, Charoen Pokphand Group Thailand (Aquaculture Innovation, 2008). It will be interesting to see the uptake of this type of product in the aquafeed sector when commercialized in the near future.

There are several benefits of microbial and plankton products. Single-cell products include products from bacteria, microalgae, protists and yeasts comprised of protein and omega-3 oils. Plankton, including copepods, euphausiids, amphipods and krill, which feed in low trophic levels, contain bioactive compounds like omega-3, bound phospholipids and axastanthin and have the potential to serve as a source of protein, oil, attractants and pigments (Hardy, 2004). However, exploitation of plankton should strike a balance to avoid negative ecological consequences to organisms in higher trophic levels.

Converting low-grade land-animal by-products into high-value aquafeed protein, with the appropriate amino acid balance, may be an innovative and a low-cost method to achieve the high levels of fishmeal replacement necessary (Aquaculture Innovation, 2008). In addition to plankton, other invertebrates used as protein sources to replace fishmeal are polychaete worms and terrestrial insects. Polychaetes include both marine worms (e.g. *Nereis virens*) and the earthworms (e.g. *Eisenia foetida* and *Endrilus eugineae*). On dry matter basis, the earthworm has 60–70 percent protein with high essential amino acid content, especially lysine and methionine. Other nutrients include 6–11 percent fat, 5–21 percent carbohydrate, 2–3 percent minerals and a range of vitamins, particularly niacin and vitamin B_{12}. Marine worms, particularly known to induce sexual maturity, are used in broodstock and maturation feeds. The main limitation is their high moisture content (60 percent) and availability. These worms are a potentially valuable source of protein if they can be produced and processed economically. Among terrestrial insects, silkworm pupae, which contain a high content of free fatty acids, are being used. The de-oiled pupae are found to be most appropriate because of their high protein content and well-balanced amino acids.

In order to overcome poor growth and reduced immunity due to replacement of fishmeal, several initiatives have been taken in the feed industry. Some of the common initiatives are listed below.

Antibiotics: Drugs of natural or synthetic origin that have the capacity to kill or to inhibit the growth of micro-organisms are administered through feed. Prophylactic antibiotics are mostly used in intensive aquaculture to bolster the immune system, which tends to be weakened by stress caused by manipulations and high stocking densities or by replacement of fishmeal. Antibiotics are also used as growth promoters because of their positive effects on weight gain, feed utilization and mortality reduction.

However, antibiotics administered through feed can find their way to the wider aquatic environment through unconsumed feed and faeces. Consequently, residual antibiotics exert selective pressure, which alters composition of the indigenous micro-flora and increases their resistance to antibiotics. Residual antibiotics have also been detected in fish and shellfish products destined for human consumption with similar consequences. This has led to stern measures against use of antibiotics ranging from total ban to severe restrictions of their use in aquaculture.

Nutrient supplementation: Poor performance in terms of immune-competence and disease resistance is partly due to deficiencies of nutrients, particularly amino acids/

proteins, vitamins and minerals. These nutrients include the amino acids, arginine, glutamine and L–tryptophan. While arginine plays a key role in the microbial killing mechanism, glutamine serves as a source of energy for the immune system and as a precursor for nucleotide synthesis and facilitates proliferation of immunocytes during infection. L–tryptophan suppresses aggression in juvenile cod and cannibalism in juvenile grouper and prevents cortisol responses to stress in rainbow trout.

Probiotics, prebiotics and synbiotics: Probiotics are applied through feed or culture medium to prevent against pathogenic bacteria by minimizing the numbers of potentially pathogenic microbes by competitive exclusion, thereby modifying the composition of the microbial community in the organism as well as the culture medium in favour of harmless/beneficial microbes. Probiotics are natural viable micro-organisms such as *Bacillus* spp bacteria that have a beneficial effect on the health of the host upon ingestion by improving properties of its indigenous microflora. In general, the gastrointestinal microbiota of fishes, including those produced in aquaculture, have been poorly characterized, especially the anaerobic microbiota and, therefore, more detailed studies of the microbial community of cultured fish are needed to potentially enhance the effectiveness of probiotic supplementation (Gatlin *et al.*, 2007).

Prebiotics are non-digestible food ingredients, which have beneficial effects on the host by selectively stimulating growth and/or activating a limited number of health promoting bacteria in the intestinal tract, thus improving the host's intestinal balance and consequently decreasing the incidence of infection (Gibson and Roberfroid, 1995). Mostly oligosaccharides, such as mannan-oligosaccharides, fructo-oligosaccharides, transgalacto-oligosaccharide and inulin act as prebiotics (Vulevic, Rastall and Gibson, 2004).

Synbiotics are mixtures of probiotics and prebiotics, which are beneficial to the host by improving the survival and implantation of live microbial dietary supplements in the gastrointestinal tract by selectively stimulating the growth and/or activating the metabolism of one or a limited number of heat-promoting bacteria and thus improving host welfare. This is a new concept in aquaculture.

Nucleotides: These are low molecular weight biological compounds, which are building blocks of DNA and RNA and play vital roles in various physiological and biochemical functions of the body, often regarded as conditionally essential nutrients particularly during periods of rapid growth and physiological stress (Uauy, 1994). Dietary nucleotides are more preferential because de novo synthesis and salvage of nucleotides are metabolically costly processes that account for 5–10 percent of the energy used in the synthesis of tissue protein (Carver, 1994; Grimble, 1994). Dietary nucleotides in aquaculture have shown a number of beneficial effects such as:

- enhanced feed intake observed in largemouth bass (Kubitza, Lovshin and Lovel, 1997);
- improvement in growth observed in tilapia (Ramadan and Atef, 1991) and salmonids (Adamek *et al.*, 1996; Burrells *et al.*, 2001);
- increased resistance to pathogens observed in salmonids (Burrells *et al.*, 2001; Leonardi, Sandino and Klempau, 2003) and hybrid striped bass (Li, Lewis and Gatlin, 2004); and
- increased resistance to stress in salmonids (Burrells *et al.*, 2001; Leonardi, Sandino and Klempau, 2003).

Acidifiers: Acidifiers are potential alternatives to antibiotics and include organic acids (formic, acetic, propionic, lactic and citric) and organic salts (calcium formate, sodium formate, potassium diformate, calcium propionate and calcium lactate). The modes of positive influence of acidifiers are:

- reducing pH of feeds, thus inhibiting growth of microbes, some of which are potentially pathogenic;
- reducing pH in the stomach and small intestines, thus improving pepsin activity particularly during periods where levels of free hydrochloric acid are reduced, e.g. during high feed intake in young animals or when animals are fed diets with high protein content; and
- supplying energy for metabolism, as organic acids contain substantial amounts of energy, e.g. propionic acid contains one to five times more energy than wheat (Diebold and Eidelsburger, 2006).

Acidifiers have been reported to positively improve performance in arctic charr (Ringø, 1991), rainbow trout (de Wet, 2005) and tilapia (Ramli, Heindl and Sunanto, 2005).

Enzymes: Feed enzyme supplements have been predominantly used in pig and poultry diets. Use of enzymes in aquaculture has been relatively low perhaps due to reliance on fishmeal as a major source of protein in aquafeeds. Fishmeal is highly digestible and, therefore, little could be gained by adding enzymes. However, the application of enzymes in aquafeed deserves adequate consideration with the increasing utilization of plant products as partial or complete replacement of fishmeal. Plant products usually contain large amounts of fibre and a number of anti-nutritional factors that limit their nutrient availability, and feed enzymes have often been used to increase nutrient availability by both releasing bound nutrients and breaking down compounds. Feed enzymes work best when they complement endogenous enzymes in breaking down compounds to a size, that can be easily utilized by the animal. In this regard, phytase has proven consistently to improve availability of P, while protease and carbohydrase enzymes have given variable responses. Gatlin *et al.* (2007) reviewed the following researchable issues and approaches to increased use of plant products in aquafeeds.

Enhancing utilization by genetic selection of fish: Of great interest is the determination of whether carnivorous fish that have a natural capacity to utilize protein as their main energy source can be genetically selected for effecting improved utilization of plant material.

Optimizing bioactive compounds: Several plant feedstuffs contain bioactive compounds that may have positive or negative effects on aquatic animals and, thus, investigations to adjust their concentrations accordingly in aquafeeds are needed.

Monitoring effects of plant feedstuffs on fish product quality and consumer health: Given the physiological, nutritional, environmental and compositional differences among farmed finfish, conclusions reached about the product quality of one species cannot be automatically applied to another species. Further research is needed to clarify the influence of dietary ingredients on the quality of each aquaculture species of interest.

Enhancing palatability of plant feedstuffs: Research regarding palatability of various feedstuffs may indicate why feed intake often is reduced when certain feedstuffs are included in fish diets, and may also suggest how processing methods are to be improved for optimizing palatability.