Utilization of Plant Proteins in Fish Diets; Effects of Global Demand and Supplies of Grains and Oilseeds

R.W. Hardy

University of Idaho, Aquaculture Research Institute, 3059F National Fish Hatchery Road, Hagerman, ID 83332 USA. E-mail: rhardy@uidaho.edu

Sustainable aquaculture seems like an oxymoron; how can aquaculture be sustainable when it requires more inputs that it yields in outputs? The same is true for any form of livestock or poultry production. The problem is in the definition of sustainable. For the purposes of this presentation, sustainable must be defined in relative terms that address the issues that lead to the perception that aquaculture, at least of carnivorous fish species, is not sustainable. The main sustainability issue, therefore, is that of use of marine resources, e.g., fish meal and fish oil, in aquafeeds. Global fish meal and oil production averaged 6.5 million metric tons (mmt) and 1.3 mmt, respectively, over the past 20 years. The percentage of annual global production of fish meal and oil being utilized in aquafeeds has increased steadily over the past 20 years from approximately 15% to 50% and 85% for fish meal and oil, respectively. About 50% of annual fish meal use in aquafeeds is used in feeds for carnivorous fish species such as salmon, trout, sea bass, sea bream, yellowtail, and so on. Another 20% is used in shrimp feeds, with the balance used in feeds for fry and fingerling carp, tilapia, catfish and other omnivorous species. The situation with fish oil is even more dramatic in that about half of annual use in aquafeeds is in high-energy feeds for salmonids. Global fish meal and oil production is unlikely to increase beyond current levels, even with increasing recovery and utilization of seafood processing waste. Thus, continued growth of aquaculture production is fundamentally unsustainable if fish meal and fish oil were to be the main protein and oil sources used in aquafeeds. Eventually, supplies would be insufficient. However, alternatives to fish meal and fish oil are available from other sources, mainly grains/oilseeds and material recovered from livestock and poultry processing (rendered or slaughter by-products). For aquaculture to be sustainable from the feed input side, these alternatives must be further developed and used. The main driver of change in aquafeed formulations is price of fish meal and oil relative to alternative ingredients.

Aquafeeds for both carnivores and omnivores fish species have always contained fish meal because until 2005, fish meal protein was the most cost-effective protein source available. Over the previous 30+ years, the price of fish meal remained within a trading range of $350 to $750 per metric ton (mt), varying in price in relation to global supply and demand. Since the mid 1980s, annual production of fish meal has been approximately 6.5 million metric tons (mmt) per year, although in El Niño years, global production decreased because landings in Peru and Chile declined. In especially bad El Niño years, production could decline below 5 mmt worldwide, whereas in years following El Niño events, production could increase to over 7.5 mmt. However, in 2006, the price of fish meal increased significantly to over $1500 per mt and since then, prices have remained above $1100, suggesting that a new trading range has been established. This has increased pressure to replace fish meal with plant protein ingredients.

Prior to 2006, many advances had been made in replacing portions of fish meal in aquafeeds with alternative protein sources and the percentages of fish meal in feeds for salmon, trout, sea bream and sea bass, all carnivores species, had decreased by 25-50%, depending on species and life-history stage. Similarly, the percentage of fish meal in feeds for omnivorous fish species also declined, especially in grow-out feeds. However, fish meal use by the aquafeed sector continued to increase because aquaculture production increased. In the early 1980s, for example, aquafeeds used approximately 10% of annual fish meal production. By 2005, aquafeeds used nearly 50% of annual fish meal production. During the same period, use in poultry and swine feeds decreased by an equal amount because less expensive alternatives, such as soybean meal and corn gluten meal, were increasingly used. Similar but less dramatic substitutions of fish meal by soybean meal and corn gluten meal occurred in salmon and trout feed. Despite changes in feed formulations for farmed fish, the dramatic increase in fish meal prices in 2006 and the sustained higher trading range that followed increased feed prices and costs of production. Today, the most pressing problem facing the aquaculture industry is the cost of feed, and there is substantial pressure on feed companies to develop less expensive formulations that maintain efficient growth at less cost per unit gain. The conventional wisdom is that this goal can only be achieved by lowering fish meal levels in feeds further.

Substituting plant protein ingredients for fish meal at levels now used has been relatively easy but substituting at higher levels is difficult. There are a number of challenges that must be overcome to maintain acceptable growth rates and feed efficiency values at higher levels of substitution of fish meal. The first is cost of plant protein concentrates. Until recently, fish meal protein was much less expensive than protein from soy or wheat concentrates, available as soy protein concentrate or wheat gluten meal. Although the increase in fish meal price made them more competitively priced after 2006, the recent increase in soybeans and wheat altered the pricing structure again, making them less competitive than they had been. Similar increases in price have occurred for soybean meal and corn gluten meal. Other plant-derived protein ingredients, such as lupin and rapeseed/canola protein concentrates, have been developed and researched as potential fish meal substitutes, but there is no significant production of any alternative protein concentrate other than those from soy or wheat.

Prices of all agricultural commodities have increased significantly over the past two years as a result of increasing demand for their use in feeds, foods, and in the case of corn, as starting material for ethanol production. For example, corn averaged $2 per bushel for a 30-year period until 2007, when it began to increase in price outside of its normal trading range. Over the past year, the cost of number 2 corn in Chicago increased from $2.09 per bushel to $5.87 per bushel. Soybeans saw a similar increase, from $5.83 per bushel in May of 2007 to $13.28 per bushel in May of 2008. Wheat jumped from $5.27 per bushel to $12.99 per bushel over the same period. Not surprisingly, prices for protein concentrates from corn, soybeans and wheat also increased. In the case of corn gluten meal (60% crude protein), the price jumped from $257 per ton to $575, while soybean meal (48% crude protein) increased from $179 to $335. These increases have also contributed to the current prices of aquafeeds, but despite these rapid increases in prices, the cost per unit protein for plant protein sources remains lower than that of fish meal protein, about $7-10 per protein unit compared to $14 for fish meal.

What has driven the costs of grains and oilseeds to levels seen today? On a macro-economic scale, demand has increased faster than supply. But what is driving demand? Certainly, in the USA, demand for corn as a seed stock for ethanol production is a factor. Currently, Brazil, the EU and the USA produce 90% of global ethanol for biofuels use. Producing a liter of ethanol requires 2.56 kg of corn; current ethanol capacity in the U.S. is 7.1 billion liters requiring 61,580,000 metric tons of corn. Legislation in the US mandates production of 36 billion liters by 2022. In 2007, 92.9 million acres of corn were planted, up 14.6 million acres from 2006 and the highest since 1944. Of the corn produced in 2007, 26.6% is destine for ethanol production. By 2016, 109,226,040 mt of corn will be used to produce ethanol in the US. This pattern is being replicated in other parts of the world. Global grain production hit record levels of 2,095,000,000,000 mt in 2007, yet supplies are barely adequate to meet demand. This supply-demand relationship is partially responsible for the high prices now seen for corn, plus increased acreage devoted to corn production in the USA has come as the expense of soybean and wheat production, resulting in record prices due to demand exceeding supplies. Increasing wheat prices are also being driven by lower production in Australia as a result of a multi-year drought. However, other drivers are also causing corn, soy and wheat prices to increase. Demand for livestock feed continues to increase, especially in China. China currently feeds 600 million swine, compared to 108 million for the USA and 240 million for the EU. China has been increasing its hog population by 8-10% per year. To put that in perspective, the annual increase in hog production in China is almost half of the entire hog population in the USA. China has neither the water or aerable land to produce the grain needed to feed its hogs and is not inclined to import meat; therefore it has been and will continue to be a huge importer of soybeans and grains.

Aquaculture production has increased tremendously over the past 15 years, as has aquafeed production from approximately 13mmt to over 30 mmt. Nevertheless, aquafeed production is less than 5% of annual global livestock feed production. Prices for commodities are also driven by speculation as commodity trading, especially in futures, has grown immensely. Any perceived disruption of future production, such as the recent development of a new species of wheat rust in Africa that has now spread to the Middle East, increases prices further.

One bright spot in the current plant protein situation is the potential for recovery and utilization of corn protein from ethanol production. Ethanol is produced from fermenting glucose from corn starch, and the most common process used to produce ethanol is the dry milling. In dry milling, the whole grain is ground, mixed with water, enzymes are added to convert starch to dextrose, and the mash is cooked to kill bacteria. Yeast is then added to convert dextrose to ethanol and

CO_2, which is recovered and sold. The ethanol is recovered by distilling the mixture, and purified by further distilling. The remaining material is separated into solubles and solids by centrifugation. Distiller's dried grains with solubles (DDGS) is made by drying the coarse material (protein, fiber and ash) with the solubles (mainly non-fermentable carbohydrates). One metric tons of corn yields 390 liters of ethanol and 295 kg of DDGS. One mt of corn contains, on average, 96 kg of protein. If a different method of ethanol production is used, namely the wet milling process, corn germ is separated to allow higher recovery of corn oil prior to fermentation. This process is used to produce corn gluten meal. The material remaining after fermentation, composed of fiber, some protein, some starch, and other non-fermentable residues, is used to produce corn gluten feed, a lower protein ingredient (28% crude protein). Current USA capacity for ethanol production is 7.1 billion gallons, or 27 billion liters, requiring 69 mmt of corn. At 9.6% crude protein, the total protein in this quantity of corn is 6.6 mmt, although actual recovery is lower. Nevertheless, there is a substantial amount of good quality corn protein currently being recovered as DDGS which could be recovered as corn gluten meal and substantially alter not only the economics of ethanol production (by-products are a significant source of revenue, nearly equivalent to revenue from ethanol) but also the amount of plant protein available for livestock and fish feed use. If new processes were used to refine corn and other grains into protein, fiber and starch fractions prior to fermentation, even higher quantities might be available.

The second challenge facing the aquafeed industry as it moves to substitute higher amounts of fish meal with plant proteins pertains to known nutritional limitations of plant proteins. Corn gluten meal is an important alternate protein source already in widespread use in aquafeeds, but corn gluten meal has limitations as a fish meal substitute, mainly due to its amino acid profile. Corn protein is highly digestible to fish, but corn is deficient in lysine, making it necessary to either supplement feeds containing high amounts of corn gluten meal with synthetic lysine, blend corn gluten meal with soy or wheat protein concentrates to produce a mixture with an amino acid profile more suited for fish, or both. Unlike proteins from oilseeds, such as soy or rapeseed/canola, corn protein concentrates do not contain anti-nutrients that limit its use in feeds. In contrast, soybean meal use is limited in feeds for salmonids and perhaps other species due to intestinal enteritis that results from prolonged use of feeds containing over 30% soybean meal. However, soybean meal contains only 48% crude protein, much lower than fish meal or plant protein concentrates, such as soy protein concentrate (~75% crude protein) or wheat gluten meal (~75-80% crude protein). The relatively low protein content of soybean meal restricts its use in high-energy diets where there is little room in the formulation for ingredients that are not relatively purified. The same holds true for DDGS. Conventional DDGS contains 28-32% crude protein, insufficient to be considered a protein concentrate. New technologies are being used to remove fiber from DDGS, thus increasing its protein content to 40% or more. This approach makes high-protein DDGS a suitable ingredient for use in feeds for omnivorous fish species but not for carnivorous fish species requiring high protein feeds for optimum growth and health.

The most promising alternate protein sources are high-protein concentrates produced from soy and wheat. Soy protein concentrate lacks the anti-nutritional properties of soybean meal and can substitute for up to 75% of fish meal in feeds for salmonid species. Worldwide, about 500,000 mt of soy protein concentrate is made, and about 70% is used in human food applications; the balance is used in pet foods and milk replacers for calves and piglets. Production could easily double to meet current and expected demand, but even at this level of production, the quantities would be insufficient to meet the expected demand in aquafeeds for 1.5-2.0 mmt of fish meal substitution by 2015. However, ethanol production has had the unexpected effect of reducing the acreage of soybean plantings in the USA, as farmers are planting more corn and fewer soybeans. Thus, emphasis on ethanol production from corn is impacting soybean production and driving up costs.

Wheat and rapeseed are the other main crops which are produced in sufficient quantity to be potential sources of protein concentrates for use in aquafeeds. Rapeseed is produced for its oil, leaving the residue available for other uses. Rapeseed/canola protein concentrates have been evaluated as fish meal substitutes with relatively good results, providing that measures are taken to enhance feed palatability and minimize the effects of glucosinolates which affect thyroid function. Wheat protein concentrate is already widely produced and sold as wheat gluten meal, but nearly all of current production is used in human food applications.

To date, various attempts to rear carnivorous species of fish using aquafeeds in which all protein is supplied by plant protein concentrates have revealed that while fish can thrive and grow rapidly on such feeds, growth is lower than when feeds containing fish meal are used. Thus, the third challenge to overcome to developing plant protein-based aquafeeds for carnivorous fish species concerns unknown nutrients and biologically-active materials in fish meal that are not present in plant protein concentrates and that may be necessary dietary constituent for optimum growth and health of fish. This challenge is similar to that facing the poultry feed industry 20-30 years ago. At that time, a small percentage of fish meal was routinely added to poultry feeds; without it, growth performance was reduced. Fish meal was said to contain unidentified growth factors that were necessary for optimum growth and efficiency. Over time, researchers identified a number of dietary constituents that were supplemented into poultry feeds, allowing formulators to lower and finally eliminate fish meal as a feed ingredient. The unidentified growth factors were primarily trace and ultra-trace elements. While the situation in aquafeeds in analogous, it is not identical in that the unidentified growth factors required be fish are less likely to be trace elements and more likely to be amines, such as taurine, and possibly steroids. Imbalances in macro and trace minerals cannot, however, be eliminated as nutritional concerns in all-plant feeds. Fish meal is rich in macro and trace elements, in contrast to plant proteins. Research is needed to identify optimum levels of required minerals and to demonstrate potential antagonistic interactions among ingredients that lower mineral bioavailability. Research is also needed to identify and test so-called ‘semi-essential’ nutrients and other biologically-active materials in fish meal.

As research findings begin to be made that allow higher levels of plant proteins to be substituted for fish meal in aquafeeds, new challenges are likely to emerge. These challenges may be related to product quality, environmental impacts of aquaculture, or the economics of production. Each of these challenges could alter the rate at which the aquafeed industry moves toward the use of more sustainable aquafeeds that contain less and less fish meal and fish oil. Fish meal will no longer be the primary protein source in aquafeeds for carnivorous fish species, but rather be a specialty ingredient added to enhance palatability, balance dietary amino acids, supply other essential nutrients and biologically-active compounds, or enhance product quality. Fish oil will be used to ensure adequate omega-3 levels in fillets for the consumer but not as a primary energy source; plant lipids will fulfill that role.