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REVIEW ARTICLE

Utilization of plant proteins in fish diets: effects of global demand and supplies of fishmeal

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Abstract

Aquafeed ingredients are global commodities used in livestock, poultry and companion animal feeds. Cost and availability are ditated less by demand from the aquafeed sector than by demand from other animal feed sectors and global production of grains and oilseeds. The exceptions are fishmeal and fish oil; use patterns have shifted over the past two decades resulting in nearly exclusive use of these products in aquafeeds. Supplies of fishmeal and oil are finite, making it necessary for the aquafeed sector to seek alternative ingredients from plant sources whose global production is sufficient to supply the needs of aquafeeds for the foreseeable future. Significant progress has been made over the past decade in reducing levels of fishmeal in commercial feeds for farmed fish. Despite these advances, the quantity of fishmeal used by the aquafeed sector has increased as aquaculture production has expanded. Thus, further reduction in percentages of fishmeal in aquafeeds will be necessary. For some species of farmed fish, continued reduction in fishmeal and fish oil levels is likely; complete replacement of fishmeal has been achieved in research studies. However, complete replacement of fishmeal in feeds for marine species is more difficult and will require further research efforts to attain.

Keywords: aquafeeds, plant protein, alternative protein, fishmeal

Introduction

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 paper, sustainable is defined in relative terms that address the issues associated with the perception that aquaculture, at least of carnivorous fish species, is not sustainable. The main sustainability issue is use of marine resources, e.g., fishmeal and fish oil, in aquafeeds. If aquaculture consumes wild fish in the form of fishmeal and fish oil at higher amounts than what is produced, then aquaculture is a net consumer of fish, not a net producer. If the reverse is true, then aquaculture is a net producer of fish. However, this does not address sustainability because fishmeal and fish oil production is finite, and at current rates of use in aquafeeds and expected growth rates of aquaculture production, eventually aquaculture's demand for fishmeal and oil will exceed annual fishmeal and fish oil production. The answer to this problem is to replace fishmeal and fish oil with alternative ingredients derived from crops such as soybeans, wheat, corn or rice.

Fishmeal and fish oil

Global fishmeal and oil production averaged 6.5 and 1.3 million metric tonnes (mmt), respectively, over the past 20 years. However, in some years production is higher and in others lower. Variability in production is associated with variability in landings of fish used to make fishmeal. The most important source of variability in landings is associated with El Niño events in the eastern Pacific Ocean that affect landings of anchoveta (*Engraulis ringens*) in Peru and, to a lesser extent, northern Chile. Landings in this area can decrease by 4–5 mmt, leading to a decrease of fishmeal production of 1 000 000 metric tonnes (mt) or more in an El Niño year. For example, in 2006, fishmeal production was 5 460 000 mt, about 1 mmt lower than the 20-year average. Consequently, aquaculture used a higher percentage of fishmeal production in 2006 than will be the case in average years. Overall, however, the percentage of annual global production of fishmeal and oil being utilized in aquafeeds has increased steadily over the past 20 years from approximately 15% to 65% and 85% for fishmeal and oil respectively (Tacon & Metian 2008). In 2006, 27% of the fishmeal used in the aquafeed sector went into feeds for marine shrimp (Table 1). Feeds for marine fish utilized 18% and salmon feeds 15% of the fishmeal used in aquafeeds. Overall, 45% of the fishmeal use in aquafeeds in 2006 was used in feeds for carnivorous fish species such as salmon, trout, sea bass, sea bream, yellowtail and other species. Surprisingly, 21% was used in feeds for fry and fingerling carp, tilapia, catfish and other omnivorous species. The situation with fish oil was even more dramatic; 88.5% of fish oil production in 2006 was used in aquafeeds (835 000 mt). The leading consumer of fish oil in 2006 was salmon feeds, utilizing 38% of global production (Table 2). Marine fish, trout and marine shrimp feeds used much of the remaining fish oil.

Global fishmeal and oil production is unlikely to increase beyond current levels, although with increasing recovery and utilization of seafood processing waste, global production could increase by 15–20%. Nevertheless, continued growth of aquaculture production is fundamentally unsustainable if fishmeal and fish oil remain the primary protein and oil sources used in aquafeeds. Sooner or later, supplies will be insufficient. However, alternatives to fishmeal and fish oil are available from other sources, mainly grains/oilseeds and material recovered from livestock and poultry processing (rendered or slaughter byproducts). For aquaculture to be sustainable from the feed input side, these alternatives must be further developed and used. The main drivers of change in aquafeed formulations are price of fishmeal and oil relative to alternative ingredients, and insufficient information on the nutritional requirements of major farmed species and bioavailability of essential nutrients that is needed to formulate feeds containing alternative ingredients.

Table 1 Estimated fishmeal use in feeds for selected species groups in 2006*

Species group	Metric tonnes (mt)	Per cent aquafeed use	Per cent total production
Marine shrimp	1 005 480	27	18
Marine fish	670 320	18	12
Salmon	558 600	15	10
Chinese carps	409 640	11	8
Trout	223 440	6	4
Eel	223 440	6	4
Catfish	186 200	5	3
Tilapia	186 200	5	3
Freshwater crustaceans	148 960	4	3
Miscellaneous freshwater carnivores	111 720	3	2
Total	3 724 000	100	68.2

*Adapted from Tacon and Metian (2008). Total fishmeal production in 2006 was 5 460 410 mt, below the 20-year average due to El Niño.

Table 2 Estimated fish oil use in feeds for selected species groups in 2006*

Species group	Metric tonnes (mt)	Per cent aquafeed use	Per cent total production
Marine shrimp	100 200	12	10.6
Marine fish	167 000	20	17.7
Salmon	359 050	43	38.1
Chinese carps	0	0	0
Trout	108 550	13	11.5
Eel	16 700	2	1.8
Catfish	33 400	4	3.5
Tilapia	16 700	2	1.8
Freshwater crustaceans	16 700	2	1.8
Miscellaneous freshwater carnivores	8350	1	0.9
Total	835 000	100	88.2

*Adapted from Tacon and Metian (2008). Total fish oil production in 2006 was 943 500 mt, below the 20-year average due to El Niño.

Aquafeeds for both carnivores and omnivores fish species have always contained fishmeal because until 2005, fishmeal protein was the most cost-effective protein source available. Over the previous 30+ years, the price of fishmeal remained within a trading range of US$400 to US$900 per mt, varying in price in relation to global supply and demand. However, in 2006, the price of fishmeal increased significantly to over US$1500 per mt and since then, prices have remained above US$1100, suggesting that a new trading range has been established. This has increased pressure to replace fishmeal with plant protein ingredients.

Production of protein and oil from grains and oilseeds

In contrast to fishmeal and fish oil, world production of grains and oilseeds has increased over the past two decades as a result of higher yields and increased plantings. In 2007, global production values for maize (corn), wheat and soybeans were 785, 607 and 216 mmt respectively (http://faostat.fao.org/site/526/default.aspx). The yield of soybean meal from crushing for oil production is approximately 2/3, making soybean meal production approximately 145 mmt, 20 times the annual production of fish meal. Plant oil production is likewise much higher than fish oil production. In 2007, palm oil was the top product at 39.3 mmt, followed by soybean oil (35.6 mmt), rapeseed oil (16.8 mmt) and corn oil (15.2 mmt). This compares to 0.98 mmt of fish oil. Yields per hectare for soybeans in the United States have progressively increased from 386 kg ha^{-1} in 1993 to 474 kg ha^{-1} in 2007, an average gain in yield of slightly over 6 kg $year^{-1}$. Yields are increased by more efficient use of fertilizer and water and gains due to plant breeding. Higher grain and oilseed production is also likely from higher plantings. Most arable land in the world is already being cultivated, but opportunities to expand exist in several areas, such as the Commonwealth of Independent States, an entity comprised of 11 former Soviet republics. This area has 13% of the world's arable land but produces just 6% of the world's crops.

Although world grain production has increased, consumption has also increased, often to levels in excess of production. This has lowered the quantity of grain reserves carried over from year to year. However, the economic downturn has changed consumption patterns by reducing consumption of soybean meal by the livestock sector, particularly in China. The outlook for aquafeeds is promising, especially in light of the fact that aquafeeds comprise $<4\%$ of total global livestock feeds. Availability of plant protein ingredients for use in aquafeeds is not an issue.

Progress with replacing fishmeal with plant proteins

Before 2006, many advances had been made in replacing portions of fishmeal in aquafeeds with alternative protein sources and the percentages of fishmeal 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 fishmeal in feeds for omnivorous fish species also declined, especially in grow-out feeds. However, fishmeal use by the aquafeed sector continued to increase because aquaculture production and therefore production of aquafeeds increased. In the early 1980s, for example, aquafeeds used approximately 10% of annual fishmeal production. By 1995 and 2005, aquafeeds used nearly 29% and 50%, respectively, of annual fishmeal 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 fishmeal 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 fishmeal prices in 2006 and the sustained higher trading range that followed increased feed prices and costs of production. Although prices have declined, the most pressing problem facing the aquaculture industry remains the cost of feed, and there is substantial pressure on feed companies to develop less expensive formulations that maintain efficient growth at lower cost per unit gain. The conventional wisdom is that this goal can only be achieved by lowering fishmeal levels in feeds further. Substituting plant protein ingredients for fishmeal to supply approximately half of dietary protein has been relatively easy but replacing higher percentages of fishmeal is difficult. There are a number of challenges that must be overcome to maintain rapid growth rates and feed efficiency values at higher levels of substitution of fishmeal.

Challenges associated with replacing fishmeal with plant proteins

The first is the cost per kilogram protein from plant protein concentrates compared with fishmeal. Until 2006, fishmeal protein was much less expensive than protein from soy or wheat concentrates, e.g., soy protein concentrate or wheat gluten meal. Although the run-up in fishmeal price made the plant proteins more competitively priced after 2006, in 2007 commodity prices increased dramatically, again making protein concentrates less competitive. Prices increased 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 US$2 per bushel for a 30-year period until 2007, when it began to increase in price outside of its normal trading range. Between mid-2007 and mid-2008, the cost of number 2 corn in Chicago increased from US$2.09 per bushel to US$5.87 per bushel. Soybeans saw a similar increase, from US$5.83 per bushel in May of

2007 to US$13.28 per bushel in May of 2008. Wheat jumped from US$5.27 per bushel to US$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 US$257 per tonne to US$575, while soybean meal (48% crude protein) increased from US$179 to US$335. However, despite those rapid increases in prices, the cost per unit protein for plant protein sources remained lower than that of fishmeal protein, about US$7–10 per protein unit compared with US$14 for fishmeal.

Commodity prices as well as fishmeal prices declined in late 2008, but they did not return to their pre-2007/07 levels. It remains to be seen if the pricing relationships between fishmeal and plant protein concentrates will adjust to favour plant proteins, or if demand for fishmeal will result in higher prices, driving a switch to higher plant protein concentrate use in aquafeeds. Other plant-derived protein ingredients, such as lupin and rapeseed/canola protein concentrates, have been developed and researched as potential fishmeal substitutes, but there is no significant production of any alternative protein concentrate other than those from soy or wheat.

Grain and oilseed prices increased unexpectedly and dramatically over 2007/08, primarily because, on a macro-economic scale, demand increased faster than supply. But what drove demand? Certainly, in the United States, demand for corn as a seed stock for ethanol production was a factor. Brazil, the European Union (EU) and the United States produce 90% of global ethanol for biofuels use. Producing a litre of ethanol requires 2.56 kg of corn; ethanol capacity in 2008 in the United States was 7.1 billion litres requiring 61 580 000 mt of corn. Legislation in the US mandated production of 36 billion litres 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% was destine for ethanol production. By 2016, 109 226 040 mt of corn will be used to produce ethanol in the United States unless legislation mandating higher production of ethanol is changed. Global grain production hit record levels of 2 095 000 000 000 mt in 2007, yet supplies were barely adequate to meet demand. This supply–demand relationship was partially responsible for the high prices now seen for corn, plus increased acreage devoted to corn production in the United States came at the expense of soybean and wheat production, resulting in record prices due to demand exceeding supplies. Increasing wheat prices were also driven by lower production in Australia as a result of a multi-year drought. However, other drivers also caused corn, soy and wheat prices to increase. Demand for livestock feed increased, especially in China. In 2008, China fed 600 million swine, compared with 108 million for the United States and 240 million for the EU. China was increasing its hog population by 8–10% per year. To put that in perspective, the annual increase in hog production in China was almost half of the entire hog population in the United States. 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 13 mmt to over 30 mmt. Nevertheless, aquafeed production is < 5% of annual global livestock feed production and therefore not a factor in grain or oilseed demand. Prices for commodities were also driven by speculation as commodity trading, especially in futures, was very active until the economic collapse of late 2008. The economic contraction experienced throughout the world in 2008/09 reduced demand for grains and oilseeds, but other disruptions continued to confound estimates of grain and oilseed supply/demand relationships.

The second challenge facing the aquafeed industry as it moves to substitute higher amounts of fishmeal with plant proteins pertains to the 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 fishmeal substitute associated with its amino acid profile and non-soluble carbohydrate content. Corn protein is highly digestible to fish, but corn is deficient in lysine, making it necessary to supplement feeds containing high amounts of corn gluten meal with synthetic lysine, or blend corn gluten meal with soy or wheat protein concentrates to produce a mixture with an amino acid profile more suited for fish. Unlike proteins from oilseeds, such as soy or rapeseed/canola, corn protein concentrates do not contain anti-nutrients that limit its use in feeds. However, the crude protein content of corn gluten meal is slightly over its 60% guaranteed minimum level. This means that 40% of corn gluten meal is composed of non-protein material, mainly non-soluble carbohydrates. Non-soluble carbohydrates are of little nutritional value to fish (Stone 2003). Corn gluten meal can be produced to contain higher protein levels if non-soluble carbohydrates are not added back to the protein fraction during manufacturing, but this practice leaves manufacturers with no outlet for the non-soluble carbohydrate fraction.

Soybean meal use is limited in feeds for salmonids and perhaps other species because of its relatively low protein content and also due to intestinal enteritis that occurs in some fish species from prolonged use of feeds containing over 30% soybean meal (Rumsey, Siwicki, Anderson & Bowser 1994; Krogdahl, Bakke-McKellep & Baeverfjord 2003). Soybean meal contains only 48% crude protein, much lower than fishmeal 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 because there is little room in formulations for ingredients that are not somewhat purified. The same holds true for distiller's dried grains with soluble (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 or high-energy feeds for optimum growth and health.

The most promising alternate protein sources to use in aquafeeds are high-protein concentrates produced from soy, wheat and other grains or oilseeds. Soy protein concentrate does not cause intestinal enteritis in salmonids and can replace up to 75% of fishmeal in feeds for salmonid species (Kaushik, Cravedi, Lalles, Sumpter, Fauconneau & Laroche 1995; Stickney, Hardy, Koch, Harrold, Seawright & Massee 1996; Refstie, Korsoen, Storebakken, Baeverfjord, Lein & Roem 2000; Storebakken, Refstie & Ruyter 2000; Refstie, Storebakken, Baeverfjord & Roem 2001). 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 fishmeal substitution by 2015. However, ethanol production in the United States had the unexpected effect of reducing the acreage of soybean plantings, as farmers switched from planting soybeans to planting corn. Thus, emphasis on ethanol production from corn lowered US soybean production. Increased production from Brazil and Argentina made up some of the shortfall in US production. 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 protein-rich residue available for other uses. Rapeseed/canola protein concentrates have been evaluated as fishmeal substitutes with relatively good results, providing that measures are taken to enhance feed palatability and minimize the effects of glucosinolates which affect thyroid function (Higgs, McBride, Markert, Dosanjh & Plotnikoff 1982). 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.

The third challenge facing the aquafeed industry as it moves higher substitution of fishmeal with plant proteins pertains to speculative and unknown nutritional limitations of plant proteins compared with fishmeal. Fishmeal is a complicated product containing essential nutrients as well as a large number of compounds that are biologically active. Feed formulators blend plant protein concentrates and supplement amino acids to ensure that the amino acid content of feeds in which fishmeal levels are reduced meets or exceeds the amino acid requirements of farmed fish. They may also supplement feeds with mineral supplements such as dicalcium phosphate or double the trace mineral premix to boost feed calcium, phosphorus and trace mineral levels when fishmeal is removed from fish feed formulations. However, this may not be enough to overcome other deficiencies or imbalances that arise when fishmeal levels are lowered in feeds. This challenge is similar to that facing the poultry feed industry 20–30 years ago. At that time, a small percentage of fishmeal was routinely added to poultry feeds; without it, growth performance was reduced. Fishmeal 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 fishmeal 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 because the unidentified growth factors required for 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. Fishmeal 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 'semi-essential' nutrients and other biologically active materials in fishmeal.

The fourth challenge associated with replacing fishmeal with plant protein concentrates is associated with anti-nutritional compounds in plant proteins. Plant protein concentrates present a mixed picture concerning anti-nutrients (Francis, Makkar & Becker 2001). Proteins produced from oilseeds, in general, contain more anti-nutrients of concern for fish than do proteins produced from grains. However, many are destroyed or inactivated by processes involved with product manufacture or during extrusion pelleting. For example, soybean meal contains compounds that cause distal enteritis in the intestinal of salmonids. However, soy protein concentrate does not cause intestinal enteritis in salmonids. The factor(s) in soybean meal responsible for enteritis is evidently removed or deactivated during the processing involved with extracting carbohydrates from soybean meal to make soy protein concentrate or soy isolates.

Other anti-nutrients in plant proteins of concern in fish nutrition are not destroyed by processing or pelleting and therefore must be mitigated by supplementation. Anti-nutrients in this category include phytic acid glucosinolates, saponins, tannins, soluble non-starch polysaccharides and gossypol. Phytic acid (myo-inositol hexakis dihydrogen phosphate) is a six-carbon sugar which contains six phosphate groups, and is the storage form of phosphorus in seeds. The phosphorus in phytic acid is not available to monogastric animals, such as humans or fish, and passes through the gastro-intestinal tract. In fish farms, this can enrich ponds or rivers into which farm effluent water is discharged, contributing to eutrophication. Phytic acid also ties up divalent cations under certain conditions, making them unavailable to fish. Thus, fish can become deficient in essential minerals, especially zinc, when the phytic acid level in feeds is high, unless the diet is fortified with extra zinc. Phytic acid is present in all plant protein ingredients, and is much higher in protein concentrates, such as soy protein concentrate, than in soybeans or soybean meal. Glucosinolates are present in rapeseed (canola) products and interfere with thyroid function by inhibiting the organic binding of iodine. Their effects on fish cannot be overcome by supplementing iodine to the diet, but they can be overcome by dietary supplementation with triiodothyronine (Higgs *et al*. 1982). Saponins are found in soybean meal and are reported to lower feed intake in salmonids (Bureau, Harris & Cho 1996, 1998). Gossypol is a constituent of cottonseed meal that is well known to cause reproductive problems in livestock and fish, including reduced growth and low haematocrit (Hendricks 2002). Non-starch polysaccharides are not toxins, but they are poorly digested by fish and may interfere with uptake of proteins and lipids. Supplementing feeds with exogenous enzymes reduces this problem but may cause another by the breakdown products from non-starch polysaccharides, namely galaxies and xylems, are poorly tolerated by fish (Stone 2003).

Phytoestrogens are another constituent of some plant proteins that may be problematic in fish feeds, although this is not clearly established. Phytoestrogens commonly detected in fish feeds are genistein, formononetin, equol and coumestrol (Matsumoto, Kobayashi, Moriwaki, Kawai & Watabe 2004). The effects of phytoestrogens in fish feeds are more likely to affect male reproduction than that of females (Inudo, Ishibashi, Matsumura, Matsuoka, Mori, Taniyama Kadokami, Koga, Shinohara, Hutchinson, Iguchi & Arizona 2004), but some evidence suggests that exposure to dietary phytoestrogens at the fry stage when sexual differentiation occurs may alter sex ratio (Green & Kelly 2008).

The final challenge associated with replacing fishmeal with plant proteins is the potential to increase the effects of aquaculture on the aquatic environment. As mentioned above, most plant protein ingredients contain non-protein fractions that are poorly digested, such as phytic acid, non-soluble carbohydrates and fibre. These materials pass through the digestive tract of fish and are excreted as feces. In freshwater farming systems, these materials may stay in ponds or be discharged into streams or rivers in flow-through farming systems. In the marine environment, they pass through pens into surrounding waters. Nutritional strategies must be developed to minimize this potential problem, along the lines of strategies developed to lower phosphorus discharges from freshwater fish farms (Gatlin III & Hardy 2002).

Summary

As research findings that allow higher levels of plant proteins to be substituted for fishmeal in aquafeeds to be made, new challenges are likely to emerge. These challenges may be related to the effects of replacing fishmeal in aquafeeds on product quality, environmental impacts of aquaculture or the economics of production. Each of these challenges could affect the rate at which the aquafeed industry moves towards the use of more sustainable aquafeeds that contain less and less fishmeal. At present, fishmeal remains the primary protein source in aquafeeds for marine species and others at the fry or fingerling stages. Fishmeal now shares the role as primary protein source in feeds for salmon and trout, and is only a minor protein source in grow-out feeds for omnivorous fish species. Depending on research findings and economics, in the near future fishmeal 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.

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