Use of Soybean Meal in the Diets of Omnivorous Freshwater Fish

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Abstract

World aquaculture production is dominated by omnivorous fish species that live in freshwater, including various carp and catfish species. Soybean meal is a prominent ingredient used in prepared diets for these species, often constituting 50 to 60% of the total formulation. Such levels of incorporation are possible due to adequate palatability of soybean meal and its excellent nutritional value for these species, including high levels of crude protein, complementary amino acid profile and relatively high nutrient digestibility. For many omnivorous freshwater species cultured throughout the world, soybean meal has largely replaced more costly protein feedstuffs in diet formulations, such as fish meal, while maintaining optimal fish production. As a result, the cost of fish production has been reduced substantially. While aquacultural production continues to expand worldwide to meet the growing demand for seafood, the use of soybean products will play an even more important role in providing high-quality protein for various fish species.

Introduction

Feedstuffs derived from soybean have been used predominantly for many years in diet formulations for the aquacultural production of numerous fish species. As a group, various freshwater fish species that exhibit omnivorous feeding behavior historically have been fed prepared diets containing relatively high levels of soybean meal (up to 60% by weight). This group of fish constitutes the largest sector of world aquaculture production by tonnage (Anonymous, 2002), and are a major user of soybean products.

Fish Species

Prominent members of this group of freshwater, omnivorous species include various cyprinids, such as the common carp (*Cyprinus carpio*), which has the historical distinction of being the first fish cultured during the fifth century B.C. in China (Stickney, 2000a). Aquacultural production of this species has been established in various countries in Asia, Europe, Africa and Latin America for many years and constitutes the largest sector of world aquaculture in terms of quantity produced (Anonymous, 2002). Various other Chinese carp species, such as the silver carp (*Hypopthalmichthys molitrix*), grass carp (*Ctenopharyngodon idella*), bighead carp (*Aristichthys nobilis*), crucian carp (*Carassius auratus gibelio*) and mud carp (*Cirrhinus mulitorella*), are produced primarily in China, although more limited production occurs in other parts of Asia and Europe (Stickney, 2000a).

The Indian carps, such as the rohu (*Labeo rohita*), mrigal (*Cirrhinus mrigala*) and catla (*Catla catla*), are another group of carp species native to the Indian subcontinent and produced predominantly there. These fish are produced primarily in fertilized ponds with the use of supplemental feeds (Stickney, 2000a).

Catfish of the genus *Ictalurus* and *Clarius* also are prominent freshwater, omnivorous species that are cultured in various parts of the world. The channel catfish (*Ictalurus punctatus*) constitutes the largest aquacultural enterprise in North America, and also is produced in Latin America and Asia (Tucker, 2000). Catfish of the genus *Clarius*, also known as the "walking catfish," are distributed throughout Southeast Asia, Africa and the Near East, and are

cultured in some European countries (Stickney, 2000b). The prominent species cultured in Asia include *Clarius batrachus* and *C. macrocephalus*; whereas, the sharptooth catfish (*Clarius gariepinus*) has been cultured in Africa and Europe. These species have been cultured at various levels of intensity in earthen ponds and recirculating water systems. The level of production intensity largely dictates the nutritional regime employed, which ranges from organic fertilization to nutritionally complete prepared diets.

Another group of warmwater, omnivorous species cultured throughout the world and comprising a large portion of global production is various tilapia species (*Oreochromis* and *Tilapia sp*.) (Stickney, 2000c). These fish are native to Africa and the Middle East, but have been cultured in tropical and temperate regions around the world. They are produced at various levels of intensity in a wide range of culture systems, and nutritional regimes are adjusted accordingly.

There are several other freshwater, omnivorous species whose aquacultural production is currently limited to specific regions of the world. One such example is the silver perch (*Bidyanus bidyanus*), a fish native to Australia that has demonstrated excellent characteristics for aquacultural production in earthen ponds.

Soybean Products

Several different products derived from soybeans have been evaluated using various fish species. These products all contain rather high levels of crude protein, ranging from 38 to 49% by weight. Soybean products are recognized for having the most balanced amino acid composition of all plant feedstuffs, and the relative amounts of indispensable amino acids in these various products are very similar when expressed as a percentage of crude protein (Lim and Akiyama, 1992). The sulfur-containing amino acids methionine and cystine are generally considered to be most limiting in soybean products compared to the quantitative amino acid requirements of most fish species (NRC, 1993).

The most widely used soybean products in aquaculture diets are the meals resulting from the removal of oil from the soybean. Solvent-extraction of the oil results in products that typically contain 44% crude protein if the soybean hulls are included or 48% crude protein without the hulls (NRC, 1993). Oil extraction of soybeans by the expeller process results in a meal containing approximately 42% protein (Li et al., 2000a). The amino acid composition of these soybean meals is similar when expressed as a percent of protein, and represents the most balanced profile of all plant proteins. Soybean meal without hulls has a reduced fiber content (approximately 3.4%) compared to the meal containing hulls (approximately 6.2%). Both of these meals have lipid content around 1% due to the efficient solvent extraction process. These two soybean meals have been used most frequently in aquafeeds and therefore will receive most of the consideration in this review.

Another soybean product commonly referred to as full-fat soybean meal (FFSBM) is produced by heat treating whole soybeans. This product has a crude protein content of approximately 38% (as-fed basis) and a lipid level of approximately 18%, providing high levels of linoleic and linolenic acids (Lim and Akiyama, 1992). FFSBM has been evaluated and incorporated into diets of warmwater, omnivorous species to a more limited extent than coldwater carnivorous species, primarily due to the more restrictive lipid levels typically included in the diets of the former species. Adequate heat treatment of FFSBM is required to inactivate the heat-labile anti-nutritional factors known to be present in raw soybeans. Several different methods of heat treatment, including boiling and dry extrusion of the whole soybeans, have been employed.

The nutritional value of properly heated FFSBM for various warmwater species is somewhat variable, based on the limited number of published studies. In mirror carp (*Cyprinus carpio*), the value of FFSBM was reported to be equivalent of commercial soybean meal or soy protein concentrate reconstituted with soybean oil (Viola et al., 1983). In contrast, Abel et al. (1984) reported that a diet containing 50% heat-treated FFSBM in place of half the fish meal in a control diet supported growth of mirror carp at only 60 to 65% of the control diet. This was attributed to an inferior amino acid balance in the test diet, and supplementation of lysine, methionine and threonine to the FFSBM diet, which enhanced the growth response of mirror carp.

Hybrid tilapia (*Oreochromis niloticus* x *O. aureus*) fed a diet in which 30% of the fish meal in the control diet was replaced with FFSBM had similar weight gain, feed efficiency, protein efficiency ratio

and protein digestibility, compared to fish fed the control diet (Shiau et al., 1990). In another study, Nile tilapia (*Oreochromis niloticus*) fed boiled FFSBM as 58.3% of diet had similar weight gain, feed efficiency, apparent protein digestibility and apparent net protein utilization as fish fed a diet with 52.4% solvent-extracted soybean meal (Wee and Shu, 1989).

Channel catfish also were reported to use FFSBM, as well as commercial soybean meal (Saad, 1979). In that pond trial, catfish fed diets containing 37.2 and 77% FFSBM in place of 50 and 100% of commercial soybean meal in the control diet had similar weight gain and protein gain, but more lipid deposition compared to fish fed the control diet. Another catfish species, *Clarius gariepinus*, also was observed to have similar weight gain and feed efficiency when FFSBM replaced as much as 44.6% peanut meal in the control diet (Baloguna and Ologhobo, 1989).

Another soybean product that has been used sparingly in the diet of most fish species is soybean protein concentrate. This product appears to be a highly nutritious protein feedstuff based on the limited evaluations conducted to date, but its cost generally makes it prohibitive to use in most diet formulations for fish. Possible exceptions might be its inclusion in diets designed for specific, time-restricted life stages such as the larval stages of some fish species (Escaffre et al., 1997).

Digestibility

The digestibility or availability of various nutrient fractions in soybean products has been evaluated in a number of omnivorous fish species. In general, the digestibility coefficients obtained for various constituents in soybean products typically have been rather high, indicating a large percentage of those constituents can be digested and absorbed by the fish for further metabolism (Table 1).

The digestibility of the protein fraction of soybean products consistently has been reported to be more than 90% for species such as common carp, channel catfish, tilapia and silver perch, with values for some

Table 1: Digestibility Coefficients of Various Soybean Products for Selected Freshwater, Omnivorous Fish Species

Feedstuff	International Feed Number	Fish Species	Digestibility Coefficient (%)				
			Dry Matter	Protein	Lipid	Carbo-hydrate	Energy
Soybean meal, solvent-extracted, with hulls	5-04-604	Channel catfish[1]		77	81		
		Blue tilapia[2]		94		54	
		Nile tilapia[3]		91			57
		Hybrid tilapia[4]		95	90		81
		Common carp		92[5], 70[6], 95[7]	74[6]	62[6]	75[6], 80[7]
Soybean meal, solvent-extracted, without hulls	5-04-612	Channel catfish		85[8], 93-97[9]			73[9]
		Silver perch[10]	75	95			78
Soybean meal, dehulled, full-fat	5-04-597	Silver perch[10]	77	92			80
Soybean, whole expeller		Silver perch[10]	84	96			84

[1] Cruz (1975)
[2] Popma (1982)
[3] Hanley (1987)
[4] Degani et al. (1997a)
[5] Pongmaneerat and Watanabe (1993a)
[6] Degani et al. (1997b)
[7] Takeuchi et al. (2002)
[8] Brown et al. (1985)
[9] Wilson and Poe (1985)
[10] Allan et al. (2000)

species at or above 95%. The protein digestibility coefficients compare favorably with those of any other high-quality protein feedstuff such as various fish meals (NRC, 1993). The availability of individual amino acids in the protein fraction of soybean products has been determined for only a few fish species such as the tabl carp, channel catfish and silver perch (Table 2). However, based on data obtained from those species, the apparent availability of all dispensable and indispensable amino acids is rather high with the lowest values averaging 81% for channel catfish and the highest values averaging between 91 and 95% for common carp and silver perch, respectively. Thus, in consideration of the rather high protein digestibility coefficients of soybean products for other omnivorous species, high availability of amino acids to those various species is expected. However, amino acid availability data should be obtained for individual species so that diets for those species can be formulated more precisely on an available amino acid basis.

Lipid digestibility in soybean meal also is rather high, with values ranging from 74 to 90% for channel catfish and common carp, respectively (Table 1). Carbohydrate digestibility in soybean products has not been determined, but presumably would be lower than the other energy-yielding nutrient groups due to the presence of non-starch polysaccharides and indigestible fiber. A carbohydrate digestibility coefficient of 54% was reported for blue tilapia (*Oreochromis aureus*). Limited digestibility of this fraction primarily is responsible for reducing overall dry matter digestibility coefficients which have been reported to range from 74 to 90% (Table 1).

Energy digestibility from various soybean products is high, with values ranging from 57 to 84% (Table 1). Based on these values, the digestible energy content of solvent-extracted soybean is typically around 3,000 kcal/kg (12,500 kJ/kg). The digestible energy in FFSBM is higher for most species due to its higher lipid content.

Ingredient Substitutions

Soybean meal, with its relatively high protein content and complementary blend of amino acids, traditionally has been evaluated compared to fish meal, which is generally considered the most nutritious protein feedstuff for aquatic animals. Due to the considerable expense of fish meals and concern regarding their limited availability as aquaculture continues to expand, evaluation of appropriate substitutes for fish meal has been a longstanding research priority (Hardy, 1999). Most of the extensive research has been conducted with some of the freshwater, omnivorous species that are well established in aquaculture. These species typically do not exhibit reduced acceptability of prepared diets containing plant feedstuffs and are generally less dependent on fish meal and other protein feedstuffs of animal origin compared to carnivorous species. Therefore, the ability to substitute soybean meal for fish meal in diet formulations for these species is substantial, as summarized in the following studies.

Early studies with common carp indicated reduction of fish meal from 15 to 5% in low-protein diets (25%) by increasing soybean meal from 15 to 35% caused growth reduction which could not be altered by supplementation of additional methionine or lipid (Viola, 1975). However, subsequent experiments (Viola et al., 1981, 1981/1982) demonstrated that total replacement of fish meal (as much as 25% of the diet) with soybean meal (as much as 45% of the diet) could be achieved by supplementation of lipid (up to 10%), methionine (0.4%) and lysine (0.4-0.5%) to the soybean meal-based diet.

Similar results were obtained in another study in which high-protein (37%) diets were evaluated with common carp (Pongmaneerat et al., 1993b). In that study, a control diet containing 45% brown fish meal was compared to diets in which the fish meal was replaced progressively with combinations of soybean meal, corn gluten meal and/or meat meal. Reducing fish meal from 45% as in the control diet to 22% along with 25% soybean meal and 10% corn gluten meal resulted in similar weight gain, feed efficiency and protein efficiency ratio (PER) of common carp. Further replacement of fish meal with the other ingredient combinations did impair the measured responses, although supplementation of lysine, methionine and threonine in a diet containing 5% meat meal, 15% corn gluten meal and 40% soybean meal and no fish meal improved weight gain and feed efficiency to 90% in fish fed the control diet.

Similar results were obtained in a second experiment in which an amino acid and methionine mixture was added to diets containing 5% meat meal, 14% corn

gluten meal and 38% soybean meal. This supplementation yielded weight gain, feed efficiency and PER responses approximately 90% of those achieved by carp fed the control diet with 45% brown fish meal (Pongmaneerat et al., 1993b). Combining soybean meal with other feedstuffs rich in amino acids, such as crustacean squilla (Oratosquilla nepa) meal, also has been reported to support rapid growth of common carp (Nandeesha et al., 1989).

Several studies conducted with young channel catfish in aquaria have shown that a complete replacement of menhaden fish meal with soybean meal in diet formulations caused some growth reduction (Andrews and Page, 1974; Mohsen and Lovell, 1990), and supplementation with lysine, methionine and cystine did not provide an improvement (Andrews and Page, 1974). However, one laboratory study reported that a diet containing soybean meal at up to 50% of diet in combination with distillers grains allowed the complete replacement of fish meal without causing growth reduction of channel catfish (Webster et al., 1992a).

Numerous subsequent experiments, in which channel catfish were grown to market size in earthen ponds, have demonstrated the complete replacement of fish meal with soybean meal or other ingredients such as cottonseed meal or meat and bone meal without any impairment in growth and feed efficiency (Robinson and Li, 1993, 1994, 1998; Reigh, 1999).

Several other experiments conducted with channel catfish in ponds have revealed that diets containing 28 to 32% crude protein primarily from soybean meal provide growth equivalent to diets containing some animal protein, such as fish meal and meat and bone meal (Robinson and Li, 1999; Robinson et al., 2000; Li et al., 2000b). These diets typically have not required supplementation of any crystalline amino acids. However, channel catfish have responded to amino acid supplementation in certain practical diets, but protein-bound amino acids are used more efficiently than crystalline amino acids (Zarate and Lovell, 1997).

The blue catfish (Ictalurus furcatus) has been shown to use diets containing high percentages of soybean meal efficiently, although initial investigation indicated complete replacement of fish meal with soybean meal caused reduced growth of juvenile fish (Webster et al., 1992b). In subsequent laboratory studies with juvenile fish, the complete replacement of menhaden fish meal (15% of the diet) was

Table 2: Apparent Amino Acid Availability Values (%) of Soybean Products for Common Carp[1], Channel Catfish[2], and Silver Perch[3]

Ingredient	Int'l Feed #	Species	Arg	Cys	His	Ile	Leu	Lys	Met	Phe	Thr	Tyr	Val
Soybean meal, solvent-extracted, with hulls	5-04-604	Common carp	95.8	88.0	92.0	90.3	92.2	92.6	91.2	93.3	87.1	92.1	89.8
Soybean meal, solvent-extracted, without hulls	5-04-612	Channel catfish	95.4		83.6	77.6	81.0	90.9	80.4	81.3	77.5	78.7	75.5
		Silver perch	97.8	94.1	96.7	94.9	94.8	96.7	95.7	95.6	95.5	96.2	94.8
Soybean meal, dehulled, full-fat	5-04-597	Silver perch	95.4	96.5	94.2	92.0	92.2	94.5	95.7	93.1	94.0	93.6	91.2
Soybean, whole expeller		Silver perch	97.6	94.0	96.8	96.9	96.4	96.9	98.1	97.3	95.5	96.4	96.5

[1]Yamamoto et al. (1998) [2] Wilson et al. (1981) [3] Allan et al. (2000)

achieved without adversely affecting weight gain or feed efficiency by increasing soybean meal from 42 to 65% of the diet (Webster et al., 1995a, 1995b). In those studies, methionine supplementation in diets without fish meal did not confer additional improvements in fish responses. Blue catfish appear to have a lower dietary protein requirement compared to channel catfish (Webster et al., 2000).

The sharptooth catfish (*Clarius gariepinus*) also have responded favorably to diets containing soybean meal. van Weerd et al. (1999) conducted a laboratory experiment in which sharptooth catfish were fed diets containing between 47 to 48% crude protein, with different amounts of fish meal and soybean meal. Weight gain and feed efficiency of fish fed diets containing 41% soybean meal and 29% fish meal were similar to that of fish fed the control diet containing 18% soybean meal and 58% fish meal. However, diets containing 69% soybean meal and 6% fish meal resulted in reduced weight gain and feed efficiency.

Tilapia generally have been shown to respond favorably to the dietary replacement of fish meal with soybean meal. Davis and Stickney (1978) conducted a 4 x 4 factorial experiment in aquaria with blue tilapia to evaluate four different combinations of soybean meal and fish meal (each constituting 0, 33, 67 or 100% of dietary protein) at each of four dietary protein levels (15, 22, 29 and 36%). Diets containing all protein combinations, except the 36% protein diet with 100% fish meal were supplemented with DL-methionine. Fish fed diets containing 36% protein experienced the greatest weight gain and feed efficiency. These responses were not influenced significantly by any combination of soybean meal to fish meal. However, at the lower dietary protein levels, a general improvement in growth and feed efficiency was seen with increasing amounts of fish meal in the diet.

In another study, Shiau et al. (1987) fed hybrid tilapia control diets formulated to contain 24 and 32% crude protein exclusively from fish meal. Experimental diets at each protein level contained soybean meal either with or without methionine supplementation (0.2 to 0.26%) to replace 30% of the fish meal protein. Fish fed the three diets containing 24% crude protein showed no differences in weight gain, feed efficiency or protein efficiency. In contrast, fish fed the 32% protein diet, with all protein from fish meal, had greater weight gain, feed efficiency and protein efficiency than fish fed the diet with 30% of its protein from soybean meal. However, methionine supplementation in the diet with soybean meal allowed tilapia to achieve similar weight gain, feed efficiency and protein efficiency as those fed the control diet.

In another series of feeding trials with hybrid tilapia, Viola et al. (1988) evaluated 30% crude protein diets containing 55 to 60% soybean meal and no animal feedstuffs along with various supplements such as oil, methionine, lysine and phosphorus. Viola et al. concluded that only phosphorus supplementation of the soybean meal-based diet was required to achieve weight gain and feed efficiency responses similar to that of fish fed a control diet containing 35% fish meal.

In two separate studies (Wu et al., 1995; Tudor et al., 1996), Nile tilapia fed diets containing from 35 to 56% soybean flour and corn gluten feed, but no fish meal, had similar weight gain and feed efficiency as fish fed diets containing as much as 6% fish meal. In a more recent study (El-Saidy and Gaber, 2002), Nile tilapia fed a diet containing 55% soybean meal supplemented with 1% methionine and 0.5% lysine significantly had better weight gain and feed efficiency than fish fed the control diet containing 20% menhaden fish meal and 30% soybean meal. Unfortunately, the need for individual amino acid supplementation in the soybean meal-based diet could not be evaluated because those diets were supplemented with both methionine and lysine. Protein digestibility of the diet containing 55% soybean meal was similar to that of the diet with 20% fish meal and 30% soybean meal.

The tambaqui (Colossoma macropomum), a rapidly growing fish native to the Amazon region, has used a diet containing 59% soybean meal efficiently, although growth and feed intake was reduced compared to fish fed a diet containing 32.8% fish meal as the main protein feedstuff (van der Meer et al., 1997).

Diet Evaluations

As reviewed in the previous section, a number of studies have been conducted to compare the nutritional value of soybean meal relative to fish meal and protein feedstuffs of animal origin. In addition to those studies, several other trials have been completed in China by the American Soybean

Association (ASA) to evaluate specific diet formulations with several different omnivorous fish species. These production trials have evaluated diet formulations with a variety of fish species using the ASA's 80:20 technology in which a high-value species of one size group is fed a prepared diet and makes up approximately 80% of total fish weight while one or more "service" species constitutes the other 20% of production. Silver carp has been most commonly used as a service species due to its efficient utilization of enhanced natural productivity supported by feeding prepared diets to the high-value species.

During 1995 and 1996, 14 different feeding trials were conducted using the 80:20 technology with crucian carp (*Carassius auratus gibelio*), pacu (*Piaractus brachyomum*), Nile tilapia and Wuchang carp or bream (*Megalobram amblycephala*) (American Soybean Association, 1996a). In seven different trials with crucian carp, a plant-protein-based diet (designated J) containing 50% soybean meal, 5% cottonseed meal, 5% rapeseed meal and 10% corn gluten produced similar or better growth compared to a diet containing 5% fish meal, 40% soybean meal, and similar amounts of the other ingredients (designated diet H). The same two diets and another containing 5% fish meal and 40% soybean meal (designated diet K) also were evaluated with pacu in two different trials. Pacu grew rapidly in the trials and no significant differences in growth rate were observed among fish fed the two diets with fish meal and the one without fish meal.

In another production trial with Nile tilapia, diet K containing fish meal provided between 13 and 17% better growth and feed efficiency compared to diet J without fish meal, although tilapia grew rapidly on both diets. However, another trial with fingerling Nile tilapia showed no growth differences in fish fed diets J and H. Three other feeding trials were conducted with bream to evaluate diets H, J and K. In those trials, bream fed the plant-protein-based diet grew as well as those fed the diets containing 5% fish meal.

The previously described plant-protein-based diet and diets containing 5 to 10% fish meal also were evaluated with several different omnivorous species in 23 cage trials during 1995 and 1996 (American Soybean Association 1996b). In these trials, the plant-protein-based diet J produced similar or better growth than diets H and K diets containing 5% fish meal in six of eight trials with Nile tilapia, five of seven trials with common carp, two of two trials with crucian carp and in a single trial with bream.

The ASA has conducted several other demonstration trials with fry, fingerling and growout diets in a number of different species spanning several years. Various carp species have been the focus of many of these trials. One demonstration trial with common carp (Cremer and Zhang, 1999a) evaluated an extruded diet (designated 32/6 growout) containing 32% crude protein and 6% lipid from 57% soybean meal, 6% corn gluten meal, 29.4% wheat products, and various oil, vitamin and mineral supplements. This diet allowed carp to grow from an average of 35 grams to 623 grams in a 150-day period with a feed conversion ratio (FCR) of 1.47:1 and a 97% survival rate. Silver carp production and survival also was quite acceptable.

Excellent results also have been obtained using soybean meal-based diets with smaller sizes of mirror carp. In one such study (Cremer et al., 2001a), mirror carp were reared from 0.6 to 2 grams using a crumbled diet (designated 41/11 fry) containing 41% crude protein and 11% lipid from 46.3% soybean meal, 15% corn gluten meal, 14% anchovy meal, 13% wheat and various oil, vitamin and mineral supplements. Then an extruded diet (designated 36/7 fingerling) containing 36% crude protein and 7% lipid from 46.3% soybean meal, 10% corn gluten meal, 8% anchovy meal, 27% wheat products and various oil, vitamin and mineral supplements was fed to the fish for the remainder of the 85-day production period. At the end of the trial, fish averaged 165 grams and their FCR averaged 1.24:1. In addition, production of silver carp also was achieved using the 80:20 production technology.

Similar trials were conducted with crucian carp from fry to fingerling (Cremer and Zhang, 1999b), and fingerling to market size (Cremer and Zhang, 1999c; Cremer et al., 2000a). Fry were fed a 41/11 crumbled diet (including 46% soybean meal and 14% anchovy meal) from 0.14 gram to approximately 10 grams, then converted to the extruded 36/7 diet (including 46% soybean meal and 8% anchovy meal) until attaining an average of 50 grams in 150 days with an average FCR of 1.8:1. Similar diets have been used to grow wuchang carp from 0.2 to 44 grams in 117 days with an FCR of

1.36:1 (Cremer et al., 2000b). At 50 grams, crucian carp were fed the 32/6 diet containing 32% protein and 6% lipid (including 53% soybean meal and no fish meal) to a market size of 200 grams with an FCR of 1.63:1 in 164 days (Cremer et al., 2000a). A similar all-plant protein diet allowed groups of crucian carp initially averaging 32, 44 and 64 grams to attain market size of 250 grams in 150 to165 days with FCR values ranging from 1.5:1 to 1.61:1 (Cremer and Zhang, 1999c).

Diets for specific stages of grass carp production also have been evaluated in China. Grass carp fry fed the 41/11 soybean meal-based crumbled diet until approximately 5 grams and then converted to the extruded 36/7 diet attained 83 grams in 121 days with an FCR of 1.12 (Cremer and Zhang, 1999d). The 32/6 extruded all-plant-protein diet also provided excellent growth of grass carp from fingerling to market size (750 grams) with an average FRC of 1.2:1 (Cremer and Zhang, 1999e). However, a diet containing 32% protein, 3% lipid and 8% fiber from 50% soybean meal and 16% soy hulls provided the most cost-effective production of grass carp in several different production trials with FCR values ranging from 1.2:1 to 1.6:1 (Cremer et al., 2000c, 2001b). Other practical diet formulations for grass carp have typically contained from 24 to 30% crude protein and routinely included approximately 50% soybean meal (Ding, 1991).

Bigmouth buffalo (*Ictiobus* sp.) is another species that has responded favorably to soybean meal-based diets and the 80:20 technology. In one demonstration, buffalo fry were fed the 41/11 crumbled diet from 0.5 to 10 grams and then converted to the 36/7 extruded diet until attaining a final average weight of 60 grams in 106 days with an average FCR of 0.93:1 (Cremer and Zhang, 1999f). The all-plant-protein 32/6 extruded diet supported growth of buffalo from 60 grams to an average of 464 grams in 120 days with an average FCR of 0.99:1 (Cremer et al., 2000d).

Channel catfish also have been cultured through various phases using soybean meal-based diets and the 80:20 pond technology. In one trial, catfish fry were fed the 41/11 diet in crumble form from initial stocking to approximately 2 grams then converted to the 36/7 extruded fingerling diet. Fry grew from 1.7 grams to an average of 49 grams in 101 days of feeding with an FCR of 0.93:1 (Cremer et al., 2000e). Channel catfish fingerlings also have exhibited excellent production efficiency to market size using the 32/6 all-plant-protein extruded diet. In one such production trial, catfish grew from 126 to 570 grams in 139 days with an FCR of 1.61:1 (Cremer et al., 2001c).

In another trial, catfish grew from 59 to 672 grams in 156 days with an FCR of 1.44:1 (Cremer et al., 2001d). The 32/6 all-plant-protein extruded diet also provided rapid growth and an average FCR of 1.6 when normal and albino channel catfish were cultured in cages (Cremer et al., 2000f). Results of these various production trials in China are consistent with the diet evaluations conducted in the United States with channel catfish grown to market size in earthen ponds. Several of these studies (Robinson and Li, 1993, 1994, 1998, 1999; Robinson et al., 2000; Reigh, 1999; Li et al., 2000) have demonstrated the complete replacement of fish meal with soybean meal or other ingredients, such as cottonseed meal or meat and bone meal without any impairment in growth and feed efficiency of channel catfish. The level of soybean meal in those diets generally is as high as 41 to 52%.

Soybean Meal Research Efforts

Potential negative effects of nitrogen, phosphorus and organic matter releases from aquaculture systems to the environment have received considerable attention in recent years (Gatlin and Hardy, 2002). Phosphorus and nitrogen of dietary origin are two primary excretory products of aquacultured organisms which are of concern because they may contribute to eutrophication of aquatic systems. Fish also produce organic wastes from undigested components of the diet that contribute to the biochemical oxygen demand of aquaculture systems. More efficient utilization of dietary phosphorus, nitrogen (from protein) and organic matter will contribute directly to reducing the environmental impact of aquaculture. This increased efficiency of nutrient utilization is particularly important as various sectors of the aquaculture industry are projected to expand and intensify production in the next decade to meet the ever-increasing demand for seafood (Tidwell and Allan, 2002).

The potential for increased use of soybean meal in aquaculture diets is substantial due to its nutritional value and cost-effectiveness compared to other protein feedstuffs. Increasing the availability of

nutrients from soybean meal could possibly enhance its aquaculture, while reducing the potential for excretion of enriching nutrients by the cultured organisms.

Phosphorus in soybean meal is primarily in its organic form as phytin phosphorus or phytate, which typically comprises approximately 67% of phosphorus in plant feedstuffs. This form of phosphorus is not readily available to monogastric animals including various fish species (NRC, 1993; Buyukates et al., 2000) because of their lack of phytase, the enzyme required to liberate phosphorus from phytate. Although diets based on soybean meal generally contain less phosphorus than diets containing animal feedstuffs, increasing the availability of phosphorus from soybean products is desirable to restrict the amount of supplemental phosphorus required in diets and also limit the amount excreted by fish into the environment.

Several studies have shown that addition of fungal phosphorus to soybean meal-based diets can effectively increase the availability of phosphorus to various fish species such as common carp (Schafer et al., 1995), channel catfish (Jackson et al., 1996; Eya and Lovell, 1997; Li and Robinson, 1997; Yan et al., 2002) and sharptooth catfish (van Weerd et al., 1999). However, the instability of phytase to heat normally encountered in feed manufacturing has restricted its use in diet formulations for fish. Nevertheless, development of low-temperature manufacturing techniques and application of phytase after extrusion has provided increased opportunities for its use in the diets of aquatic species. At this time the other primary constraint for supplementing phytase in diets for aquatic species is the cost of the enzyme. Another approach to limit the amount of phytin phosphorus in soybean meal is to develop low phytic acid mutations as has been done for other important agronomic crops, such as corn and barley (Sugiura et al., 1999).

Soybean meal also contains non-starch polysaccharides, such as galactomannan, that are not digested efficiently by most monogastric animals, including fish. The use of exogenous enzymes, such as xylanase, α-galactosidase, β-glucanase and endo-β-mannanase, to make this oligosaccharide fraction more digestible has shown positive results in some terrestrial species such as poultry (Ward and Fodge, 1996; Lobo, 1999a). Enhanced digestion of this fraction in soybean meal would not only increase the digestible energy of this feedstuff, but also limit the amount of organic wastes excreted by the fish. The physical constraint of applying these heat-labile enzymes to aquafeeds produced by extrusion processing will be the same as previously mentioned with phytase supplementation (Lobo, 1999b).

Another area of research that needs to be addressed in greater detail is determining the availability of amino acids in soybean meal with more omnivorous species. Information currently is available for only a few species and has been obtained in a limited number of experiments. More information concerning amino acid availability of soybean meal to various species may allow for more flexibility in using soybean meal as well as assist in refinement of diet formulations. Increasing this base of information may result in more precise formulation of diets on an available amino acid basis so that the amino acid requirements of the fish can be met more accurately. Such refinement also may increase the efficiency of amino acid utilization by the fish and thus limit nitrogen excretion into the environment.

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Managed Aquaculture Program

This technical review paper was created through the Managed Aquaculture Marketing and Research Program (AquaSoy Initiative), funded through the United Soybean Board and American Soybean Association. The AquaSoy Initiative is designed to remove the barriers to soybean meal use in diets fed to aquaculture species. The program has been divided into two components, one focused on awareness, the other on research.

The awareness program initially focuses on Southeast Asia and India, where there are significant opportunities to intensify production within established aquaculture industries with the use of soybean meal-based diets.

The focus of the research component is salmonids, specifically rainbow trout and Atlantic salmon, and commercial crustaceans, all of which are large industries currently underutilizing soybean meal. The highly integrated and collaborative nature of this initial series of projects should result in expansion of soybean meal into new rapidly growing existing markets in North America, Europe and Asia.

This paper is one of a series of four technical review papers prepared by aquaculture specialists that summarize soy product use and potential in the diets for key aquaculture species groups. The technical reviews address the following species groups: 1) freshwater omnivorous fish; 2) marine fish; 3) marine shrimp; and 4) salmonids. All of these papers can be viewed at **www.soymeal.org**.

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