NUTRITION OF AQUACULTURE SPECIES[1]

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ABSTRACT

Dietary requirements for amino acids and fatty acids have been reported for channel catfish (*Ictalurus punctatus*), salmonids (*Oncorhynchus* spp.), common carp (*Cyprinus carpio*), tilapias (*Oreochromis* spp.), and eel (*Anguilla japonicus*). Most of the vitamin and mineral requirements are available for channel catfish and salmonids, and some are available for common carp, tilapia, eel, and other finfish and crustaceans. From this available information, cost-effective feeds can be formulated for the major commercial aquaculture species. Major differences in nutrient requirements between fish and mammals or birds are as follows: fish have a lower digestible energy:protein ratio (8 to 10 kcal of DE/g of CP for fish vs 15 to 20 kcal of DE/g of CP for livestock); fish require n-3 fatty acids and land animals require n-6; fish can absorb minerals from the water, which negates the need for some minerals in the diet; and fish have limited ability to synthesize vitamin C and must depend on a dietary source. Areas for further research include 1) refinement of nutrient requirements of the major culture species considering effects of fish size, temperature, and management; 2) nutrient requirements of crustaceans; 3) effects of nutrition on fish health and product quality; and 4) feeding technology.

Key Words: Aquaculture, Nutrition

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Introduction

The nutrients required by fish (finfish and crustaceans) for growth, reproduction, and other normal physiological functions are similar to those required by land animals. Fish need to consume protein, minerals, vitamins and growth factors, and energy sources. These nutrients may come from natural aquatic organisms or from prepared diets. If fish are held in confinement where natural foods are restricted, such as raceways, their diet must be nutritionally complete; however, where natural food is available and supplemental diets are fed for additional growth, the diets may not have to contain all the essential nutrients.

Nutritional requirements of fish do not vary greatly among species. Notable exceptions are differences in essential fatty acids, requirements for sterols, and the ability to assimilate carbohydrates. The quantitative nutrient requirements that have been derived for several species are probably an adequate basis for estimating the nutrient needs of others. As more information becomes available on nutrient requirements of various species, the recommended nutrient allowances of diets for specific needs of individual species will become more refined.

Protein and Amino Acids

Fish are fed higher percentages of protein in their diets than are land animals. The reason for this is not that fish have higher protein requirements than land animals, but that fish have lower energy requirements. As shown in Table 1, broiler chickens will consume on a kilogram of BW basis about 3.4 times as much energy but only 1.6 times as much protein as growing channel catfish. Production diets for cultured fishes will contain 30 to 35% protein with a good amino acid balance, whereas this type of feed for poultry or pigs will contain 18 to 23 or 14 to 16%, respectively.

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TABLE 1. COMPARISON OF DAILY CONSUMPTION PER KILOGRAM OF BODY WEIGHT OF FEED, PROTEIN, AND ENERGY BETWEEN BROILER CHICKEN (.8 kg) AND CHANNEL CATFISH (.1 kg)[a]

Animal	Feed, g	Energy, kcal ME[b]	Protein, g
Broiler chicken	89	284	17.8
Channel catfish	30	83	10.8
Ratio: chicken/catfish	3/1	3.4/1	1.6/1

[a]Sources: NRC (1983, 1986).

[b]ME adjusted from DE for channel catfish.

TABLE 2. PROTEIN AND DIGESTIBLE ENERGY (DE) REQUIREMENTS OF VARIOUS SIZES OF CHANNEL CATFISH FOR MAXIMUM PROTEIN SYNTHESIS[a]

Fish size, g	Protein, g·100 g fish^{-1}·d^{-1}	DE, kcal·100 g fish^{-1}·d^{-1}	DE:CP ratio, kcal:g
3	1.64	16.8	10.2
10	1.11	11.4	10.3
56	.79	9.0	11.4
198	.52	6.1	11.7
266	.43	5.0	11.6

[a]Source: Mangalik (1986).

Mangalik (1986) found that daily protein requirement per 100 g of BW for maximum growth of channel catfish decreased significantly as size increased, from 1.64 g/kg for 3-g fish to .43 g/kg for 266-g fish (Table 2). Digestible energy requirement decreased at almost the same rate, so that the DE:CP ratio changed only slightly as fish size increased from 3 to 266 g.

Fish require the same 10 essential amino acids as warm-blooded animals. Quantitative amino acid requirements have been established for five fish species (Table 3). Except for arginine, which fish synthesize poorly in comparison with swine, the amino acid requirements of fish are relatively similar to those of other animals.

The research literature is unclear on the efficacy of supplementing fish diets with crystalline amino acids. Rumsey and Ketola (1975) reported that individual supplementation of soybean meal with lysine, methionine, histidine, or leucine did not improve growth rate of rainbow trout but that collective supplementation did increase growth rate. Fordiani and Ketola (1980) found that methionine supplementation of commercial soybean meal improved growth rate of rainbow trout, but that methionine supplementation did not improve reheated soybean meal. Viola et al. (1982) reported that supplementation of soybean meal with both methionine and lysine improved carp diets. Wilson (personal communication) fed crystalline lysine with peanut meal, which is severely deficient in lysine for channel catfish, and found an improvement in growth response.

Generally, fish do not seem to utilize dietary crystalline amino acids as well as chickens, or at least not with conventional once-per-day feeding practices. Young carp fed once daily a diet containing a high level of crystalline amino acids excreted up to 40% of the free amino acids intact through the gills and kidneys (Murai, 1985). Increasing the feeding frequency to four times daily improved utilization of the crystalline amino acids. This supports the concept that an important reason fish do not utilize supplemental crystalline amino acids well, especially when only one or two are fed, is that crystalline amino acids fed once per day are not absorbed from the gut with the amino acids from ingested protein.

Soybean meal is currently the major protein source for catfish feeds in the United States. The protein has a favorable amino acid profile for channel catfish (NRC, 1983), but substituting fish meal into soybean meal-grain diets for channel catfish improves growth (Andrews and Page, 1974; Murray, 1982). Currently, commercial catfish feeds contain 5 to 10% whole fish meal. Substitution of other animal protein sources, such as meat and bone meal, in all-plant diets for channel catfish improves growth by mechanisms other than supplying limiting amino acids (Mohsen and Lovell, 1990).

Energy

One of the striking differences in nutrition between fish and farm animals is that the amount of energy required for protein synthesis is much less for fish than for warm-blooded food animals (Table 4) (NRC, 1983). Fish have lower dietary energy requirements because they exert relatively less energy to maintain position and to move in water than do mammals and birds on land (Tucker, 1969), and because they excrete most of their nitrogenous wastes as ammonia instead of urea or uric acid, thus losing less energy in protein catabolism and excretion of nitrogenous waste

TABLE 3. AMINO ACID REQUIREMENTS OF CHANNEL CATFISH, SALMONIDS, CARPS, TILAPIAS, AND EELS AS PERCENTAGES OF DIET (AS-FED BASIS)[a]

Item	Channel catfish	Salmonid	Carp	Tilapia	Eel
Energy base[b], kcal DE/kg diet	3,000	3,600	3,200	3,000	4,200
Digestible protein, %	32	34	35	32	44
Arginine, %	1.38	1.51	1.50	1.34	1.98
Histidine, %	.48	.65	.74	.54	.92
Isoleucine, %	.83	.86	.88	.99	1.76
Leucine, %	1.12	1.41	1.16	1.09	2.33
Lysine, %	1.63	1.80	2.00	1.63	2.33
Methionine + cystine, %	.74	1.04	1.09	1.02	1.41
Phenylalanine + tyrosine, %	1.60	1.84	2.28	1.82	2.55
Threonine, %	.64	.79	1.37	1.15	1.76
Tryptophan, %	.16	.18	.28	.32	.48
Valine, %	.96	1.15	1.26	.90	1.76

[a]Source: NRC (1991).

[b]Typical energy concentrations in practical diets.

(Goldstein and Forster, 1970). Thus, maintenance energy requirement and heat increment are lower for fish than for land animals. Metabolic heat production (kcal/24 h) for small (4 g) rainbow trout was 57 kcal/kg $BW^{.63}$ (Smith et al., 1978) vs 70 to 83 kcal/kg $BW^{.75}$ for mammals and birds (Brody, 1945). Smith et al. (1978) measured heat increment by direct calorimetry and found it to be 3 to 5% of ME for rainbow trout; in mammals it may account for as much as 30% of ME (Brody, 1945).

Derived energy requirements of warm-water fish have usually been reported as a function of dietary protein level. Garling and Wilson (1976), using purified diets, reported the optimum DE:CP (kcal/g) ratio for growth of small channel catfish to be 9.6, and Page and Andrews (1973), using practical diets, also found a value of 9.6. Lovell and Prather (1973) found the optimum DE:CP ratio to be 7.8 for practical diets to grow channel catfish to a harvestable size of .5 kg. The optimum DE:CP ratio for small common carp was reported to be 8.3 (Takeuchi et al., 1979). These ratios compare to 15 kcal for poultry and 19 kcal for pigs, per gram of protein (NRC, 1986, 1988).

Fish utilize proteins and triglycerides effectively as energy sources. Warm-water fishes digest grain carbohydrates (starches) relatively well, but cold-water species digest them poorly. Gross energy in uncooked starch is about 20% digestible by rainbow trout but approximately 60% digestible by channel catfish (NRC, 1983). Cooking, as in extrusion processing of fish feeds, increases the digestibility of starch for channel catfish by 5 to 50% (Cruz, 1975). Metabolizable energy in highly digestible, concentrated protein feedstuffs is higher for fish than for farm animals (Smith, 1976) because of the lower energy loss in excretion of nitrogenous wastes.

TABLE 4. ENERGY REQUIREMENT FOR PROTEIN SYNTHESIS BY FISH AND WARM-BLOODED ANIMALS[a]

Food animal	Dietary protein, %	Dietary ME[b], kcal/kg	Protein gain/Mcal of ME consumed, g
Channel catfish	32	2.9[b]	47
Broiler chickens	20	2.9	23
Swine	16	3.1[b]	9
Beef cattle	11	2.6	6

[a]Source: NRC (1983).

[b]ME: estimated from DE.

TABLE 5. VITAMIN REQUIREMENTS FOR CHANNEL CATFISH, SALMONID, CARP, TILAPIA, AND EEL[a]

Vitamin	Unit	Channel catfish	Salmonid	Carp	Tilapia	Eel
Vitamin A	IU/kg	1,000–2,000	2,500	4,000	NT	NT
Vitamin D	IU/kg	500	2,400	NT	NT	NT
Vitamin E	IU/kg	50	50	250	50	NT
Vitamin K	mg/kg	R	10 E	N	NT	NT
Riboflavin	mg/kg	9	4	7	NT	R
Pantothenic acid	mg/kg	10–15	12	25	NT	R
Niacin	mg/kg	14	20	20	NT	R
Vitamin B_{12}	mg/kg	R	.01	N	NT	R
Choline	mg/kg	400	1,000	500	NT	R
Biotin	mg/kg	R	.1	1	NT	R
Folacin	mg/kg	1	R	N	NT	R
Thiamin	mg/kg	1	1	R	NT	R
Vitamin B_6	mg/kg	3	3	6	NT	R
Inositol	mg/kg	N	300	500	NT	R
Vitamin C	mg/kg	25–50	50	R	50	R

[a]R = required in diet but quantity not determined. N = no dietary requirement demonstrated under experimental conditions. NT = not tested. E = estimated. Source: NRC (1991).

Vitamins

Vitamin C is an important nutrient in fish feeds. Whereas most land animals do not require it in their diets, fishes are extremely sensitive to a deficiency. Effects of ascorbic acid deficiency in fishes are well known and include reduced growth rate, physical deformities (scoliosis and lordosis), slowed wound healing, and reduced resistance to infections, environmental contamination (nitrites, chlorinated hydrocarbons, etc.), and other stresses (NRC, 1981, 1983). The dietary requirement for normal growth and to prevent deficiency signs is 25 to 50 mg/kg; however, increasing this by three times improves wound healing (Lim and Lovell, 1978) and increasing it 10 times increases immunity against bacterial infection (Li and Lovell, 1985).

All 15 of the vitamins listed in Table 5 have been found to be essential in diets of fish; however, all fish do not require all 15 of the vitamins. Trout require all 15 (NRC, 1981); channel catfish require all but inositol (Burtle and Lovell, 1989). Some of the B-vitamins are synthesized by intestinal bacteria in warmwater fish, such as tilapia, which do not show a dietary requirement for vitamin B_{12} (Lovell and Limsuwan, 1982). Quantitative vitamin requirements have been determined for only a few species, and complete vitamin requirements have not been determined even in those species. Commercial diets for intensively cultured fish are usually supplemented with all of the vitamins listed in Table 5 except inositol and biotin, which are usually found in sufficient quantities in fish feed ingredients.

Common deficiency signs of the vitamins essential for fish species are decreased appetite and reduced growth rate. Other signs common to several vitamin deficiencies are anemia, abnormal skin pigmentation, ataxia, hypersensitivity, hemorrhage, fatty livers, and increased susceptibility to bacterial infections. Only a few vitamins show characteristic clinical deficiency signs in fish.

Minerals

Fish can obtain minerals from the water across the gill membrane or, in the case of marine fishes that drink water, by absorption from the gut. Fish can obtain most of their calcium requirement, and, in sea water, some of their requirement for iron, magnesium, cobalt, potassium, sodium, and zinc can be obtained from the surrounding water (NRC, 1981, 1983). Channel catfish can absorb essentially all their required calcium from the water when dissolved calcium ion is 5 mg/liter or higher (Lovell, 1978). Fish usually require a dietary source of phosphorus to meet their relatively high metabolic requirement because levels of dissolved phosphorus in natural water are relatively low. The dietary requirements for several minerals by channel catfish are presented in Table 6.

TABLE 6. DIETARY REQUIREMENTS FOR PHOSPHORUS, MAGNESIUM, ZINC, MANGANESE, AND SELENIUM IN CHANNEL CATFISH

Element	Amount	Source
Phosphorus, %	.45	Lovell, 1978
Magnesium, %	.05	Gatlin et al., 1982
Zinc, mg/kg	20 or 150[a]	Gatlin and Wilson, 1983
Selenium, mg/kg	.25	Gatlin and Wilson, 1984
Manganese, mg/kg	2.40	Gatlin and Wilson, 1986a
Copper, mg/kg	5.00	Gatlin and Wilson, 1986b
Iron, mg/kg	30.00	Gatlin and Wilson, 1986c

[a]20 mg/kg is the basal requirement; 150 mg/kg is recommended in practical fish feeds to compensate for mineral and phytate binding of zinc.

Fish that do not have an acidic stomach, such as carp, do not utilize mineral sources of low solubility. For example, rainbow trout, which have a true stomach, digested 74% of the phosphorus in fish meal, whereas the stomachless carp digested only 24%; both fishes digested 94% of the phosphorus in monocalcium phosphate (Ogino et al., 1979).

Zinc deficiency produces cataracts in rainbow trout (Ogino and Yang, 1978). Ketola (1979) produced bilateral lens cataracts in rainbow trout by feeding diets containing fish meal with high bone-ash content, although the diets contained 60 mg of zinc/kg (the normal requirement is about 20 mg/kg). He corrected the problem by supplementing more zinc in the diet and speculated that the high level of calcium or other minerals in the fish meal impaired zinc absorption.

Hilton et al. (1980) reported that a dietary concentration of 13 mg/kg of selenium reduced growth rate and increased mortalities in rainbow trout. This was about 100 times the requirement for normal growth and health. Gatlin and Wilson (1984) found similar results in channel catfish.

Essential Lipids

Fish differ from warm-blooded animals in that they have a requirement for omega-3 (n-3) fatty acids. Salmonids require approximately 1% of n-3 fatty acids in their diet for maximum growth rate (Castell et al., 1972). Warm-water fishes, such as channel catfish, also have an n-3 fatty acid requirement, but they seem to be less sensitive to a deficiency than cold water species (Satoh et al., 1989). Some fishes require a mixture of n-3 and n-6 fatty acids, or, as in the case of *Tilapia zilli*, n=6 fatty acids only (Kanazawa et al., 1971). A possible reason that fish, especially cold water species, require n-3 instead of n-6 fatty acids is that the n-3 structure permits a greater degree of unsaturation, which is necessary in the membrane phospholipids to maintain flexibility and permeability characteristics at low temperatures.

Finfish readily synthesize sterols from acetate and mevalonic acid (Hazel and Sellner, 1979); however, crustaceans have limited ability to do this and therefore have a dietary requirement for sterols (Kanazawa et al., 1971; Deshimaru et al., 1979). The dietary requirement for sterol, as cholesterol, for penaeid shrimp (Kanazawa et al., 1971) and lobster (Castell et al., 1975) is .5%. Marine crustaceans seem also to require the phospholipid lecithin in their diet for growth and survival (Kanazawa et al., 1971).

Practical Feeding

Feeding fish in their aqueous environment takes on dimensions beyond those considered in feeding land animals. These include the nutrient contribution of natural aquatic organisms in pond cultures, the effect of feed input on water quality, and the loss of nutrients if feed is not consumed immediately. Early aquaculture depended primarily on natural aquatic foods as sources of nutrients (Lovell et al., 1978). As culture technology evolved, there was trend toward higher yields and faster growth, which necessitated enhancing the pond food supply by fertilization, supplementing pond foods with crude or concentrated feed materials, or providing all the nutrients to the fish in a prepared feed. As the fish become less dependent on natural food organisms and more dependent on prepared feeds, the need for nutritionally complete foods becomes more critical. In highly modified environments, such as net pens, suspended cages, and raceways

TABLE 7. TYPICAL PRODUCTION FEEDS FOR CHANNEL CATFISH AND SALMONIDS[a]

Ingredient	Extruded catfish feed, %	Salmonid GR6-30[b], %
Fish meal (herring, anchovy, menhaden)	4.0	30.0
Meat and bone meal	4.0	—
Spray-dry blood meal	—	10.0
Dehulled soybean meal	48.2	25.0
Grain or grain byproducts	41.45	—
Wheat middlings	—	17.25
Wheat flour	—	5.0
Fat or oil	1.0	10.0
Trace mineral mix	.1	.1
Vitamin mix	.25	.65
Pellet binder	—	2.0
Dicalcium phosphate	1	—
Proximate composition		
Crude protein	32	42
Crude fat	4.5	13

[a]Sources: Channel catfish, Lovell, 1989; salmonids, Hardy, 1989.

[b]U.S. Fish and Wildlife Service salmonid grower diet formula.

and in intensively stocked ponds, nutritionally complete feeds are needed. Some low-yield aquaculture practices, such as low-density carp and tilapia culture in some developing countries, rely heavily on natural aquatic food as source of nutrients for fish growth; however, most aquaculture today involves feeding nutritionally balanced feeds (Lovell, 1989).

Because fish are fed in water, feed that is not consumed within a reasonable time represents not only an economic loss but also reduces water quality. Therefore, feed allowance, feeding method, and water stability of the feed are factors that the fish cultures must consider but that the livestock feeder does not. Commercial feeds should be processed into pellets that will remain intact in water until consumed by the fish. Pellets with long water stability are especially important for slow-feeding species such as shrimp.

Catfish farmers in the United States prefer floating feeds. This is a valuable management tool when raising fish in ponds because it allows the fish farmer to determine how much the fish are consuming and also allows the farmer to gauge the condition of the fish and water quality on the basis of feeding activity. Most fishes accept surface feeds satisfactorily, but some species, such as penaeid shrimps, prefer sinking feeds. Diet texture is important for some fishes. Most commercially cultured species accept dry feed particles but some fish, such as eels and young salmon, prefer soft diets that contain 30 to 40% pasteurized animal flesh (Hardy, 1989).

Contemporary feeds for omnivorous species, such as channel catfish and common carp, contain only small amounts of animal protein ingredients, whereas those for carnivorous species, such as salmonids, contain larger amounts. Comparison of typical feed formulations for channel catfish and salmonids (Table 7) shows that catfish feeds contain principally grain (corn) and soybean meal with relatively small amounts of animal protein and fat. Salmonid feeds, however, contain large amounts of fish meal with a relatively low amount of starch but a high content of oil as an energy source.

Occasionally fish are fed with demand feeders that allow them to eat ad libitum, but usually they are fed measured allowances once or twice daily, the amount being based on the

TABLE 8. FEED CONVERSION, GROWTH RATE, AND FEED CONSUMPTION FOR DIFFERENT SIZES OF CHANNEL CATFISH DURING THREE CONTINUOUS GROWTH PERIODS IN EARTHEN PONDS[a]

Criterion	Initial fish size, g	June	July	August	Overall
Feed conversion, kg feed/kg gain	45	1.25	1.35	1.51	1.43
	150	1.27	1.58	1.82	1.67
	550	1.82	2.39	2.08	2.16
Growth increase, percentage of initial wt	45	229	391	688	
	150	202	274	405	
	550	118	134	169	
Daily feed consumption, percentage of BW	45	3.0	2.4	1.6	
	150	2.6	1.6	1.5	
	550	1.2	1.4	1.2	

[a]Source: Cacho, 1984.

judgment of the feeder. Feed allowance and frequency of feeding decrease as fish size increases from hatch to harvestable size. For example, channel catfish fry (0 to 3 wk) in the hatchery are fed 5 to 10% of BW/d in 10 or more daily feedings; fingerlings, or first-year fish (up to 50 g), are usually fed twice daily at rates of 3 to 5% of BW; and fish in production ponds are fed once daily at rates of 1.2 to 3.0% of BW (Dupree and Huner, 1984; Lovell, 1989).

Table 8 presents a summary of data (from Cacho, 1984) indicating the effect of increase in fish size on feed consumption, growth rate, and feed efficiency in channel catfish. All responses decreased as fish size or feeding period increased. This relationship between size and response will be similar in other fish species as they grow from fingerling to harvestable size.

Implications

Sufficient information is available on dietary requirements for amino acids, fatty acids, vitamins, minerals, and energy to formulate cost-effective feeds for the major commercial aquaculture species. However, to maximize economic and nutritional efficiency, additional research is necessary on the following subjects: 1) refinement of nutrient requirements for the major culture species considering effects of fish size, temperature, and management; 2) nutrient requirements for crustaceans; 3) effects of nutrition on fish health and consumer product quality; and 4) feed technology.

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