Shrimp Farming and the Environment

Thematic Review of Feeds and Feed Management Practices in Shrimp Aquaculture

A Consortium Program of:

THEMATIC REVIEW OF FEEDS AND FEED MANAGEMENT PRACTICES IN SHRIMP AQUACULTURE

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Preparation of this document

The research reported in this paper was prepared under the World Bank/NACA/WWF/FAO Consortium Program on Shrimp Farming and the Environment. Due to the strong interest globally in shrimp farming and issues that have arisen from its development, the consortium program was initiated to analyze and share experiences on the better management of shrimp aquaculture in coastal areas. It is based on the recommendations of the FAO Bangkok Technical Consultation on Policies for Sustainable Shrimp Culture[1], a World Bank review on Shrimp Farming and the Environment[2], and an April 1999 meeting on shrimp management practices hosted by NACA and WWF in Bangkok, Thailand. The objectives of the consortium program are: (a) Generate a better understanding of key issues involved in sustainable shrimp aquaculture; (b) Encourage a debate and discussion around these issues that leads to consensus among stakeholders regarding key issues; (c) Identify better management strategies for sustainable shrimp aquaculture; (d) Evaluate the cost for adoption of such strategies as well as other potential barriers to their adoption; (e) Create a framework to review and evaluate successes and failures in sustainable shrimp aquaculture which can inform policy debate on management strategies for sustainable shrimp aquaculture; and (f) Identify future development activities and assistance required for the implementation of better management strategies that would support the development of a more sustainable shrimp culture industry. This paper represents one of the case studies from the Consortium Program.

The program was initiated in August 1999 and comprises complementary case studies on different aspects of shrimp aquaculture. The case studies provide wide geographical coverage of major shrimp producing countries in Asia and Latin America, as well as Africa, and studies and reviews of a global nature. The subject matter is broad, from farm level management practice, poverty issues, integration of shrimp aquaculture into coastal area management, shrimp health management and policy and legal issues. The case studies together provide a unique and important insight into the global status of shrimp aquaculture and management practices. The reports from the Consortium Program are available as web versions (http://www.enaca.org/shrimp) or in a limited number of hard copies.

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[1] FAO. 1998. Report of the Bangkok FAO Technical Consultation on Policies for Sustainable Shrimp Culture. Bangkok, Thailand, 8-11 December 1997. FAO Fisheries Report No. 572. Rome. 31 p.

[2] World Bank. 1998. Report on Shrimp Farming and the Environment – Can Shrimp Farming be Undertaken Sustainability? A Discussion Paper designed to assist in the development of Sustainable Shrimp Aquaculture. World Bank. Draft (Available at www.enaca.org/shrimp).

Abstract

This paper reviews feeds and feed management practice in shrimp aquaculture. The review describes feeds and feed management practices in different shrimp farming systems, and assesses the trends in feed use in shrimp aquaculture and environmental implications feed use. Particular attention is given to the use of fish meal in shrimp diets and water pollution caused by feeds. The review then identify practices at farm, manufacturing and ecosystem levels that can reduce environmental impacts associated with the use of shrimp feeds, giving special attention to fish meal and effluent management, and practical measures that can be taken to promote more efficient use of feed resources. It then analyzes the constraints and opportunities for promoting better practices, including costs and benefits for their adoption and identifies some follow up activities to support efficient use of feed resources, including nutrition and feed management research, information exchange, and others.. The paper also explores the recent assertions that shrimp aquaculture is literally "feeding on world fisheries" and that the production of shrimp contributes to net loss of wild caught fish. Trends in the use of alternative ingredients to replace fish meal, including soybean meal, and other agricultural byproducts, are also considered. The paper also provides a comprehensive set of references for further reading on the subject.

Content

Abbreviations and Acronyms

ADB	Asian Development Bank
CCRF	FAO's Code of Conduct for Responsible Fisheries
EFS	Extensive Farming Systems
FAO	Food and Agriculture Organization (of the United Nations)
FCR	Feed Conversion Ratio
ha	Hectare
IFN	International Feed Number
IFOMA	International Fish meal and Fish Oil Manufacturers Association
IFS	Intensive Farming Systems
kg	Kilogram
mg	Milligram
MMT	Million metric tons
MT	Metric tons
N	Nitrogen
NACA	Network of Aquaculture Centres in Asia-Pacific
OI	Ocean Institute in Hawaii
P	Phosphorus
PCB	Polychlorinated biphenyls
PCDD	Polychlorinated dibenzo-p-dioxins
PCDF	Polychlorinated dibenzofurans
pg	Picogram
PL	Post larvae
ppm	Parts per million
SCP	Single Cell Protein
SEAFDEC	Southeast Asian Fisheries Development Center
SIFS	Semi-intensive Farming Systems
SPF	Specific pathogen-free
TSS	Total suspended solids
US$	American dollars
WB	World Bank
WWF	World Wildlife Fund

Introduction: Overview of Global Shrimp Aquaculture Production

Shrimp farming is one of the most profitable and fastest-growing segments of the aquaculture industry. Global farmed shrimp production has grown over 100-fold (by weight) in less than two decades, from under 10,000 metric tons (MT) produced by fewer than a dozen countries in the early 1970s to over 1 million MT (MMT) by the late 1990s (Figure 1).

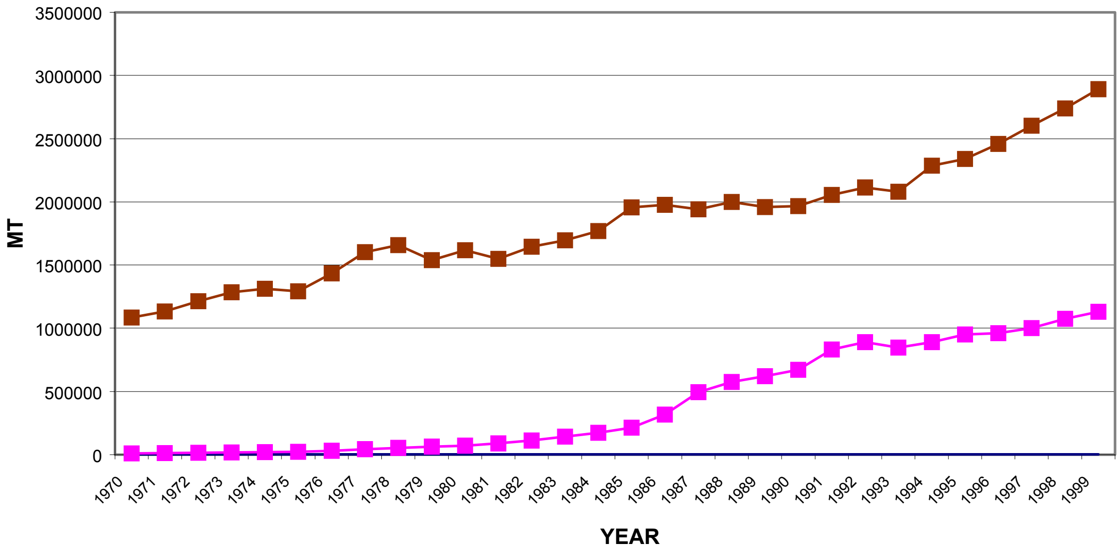


Figure 1. Total global shrimp landings from capture fisheries (dark line) and aquaculture (light line). Growth (expressed as % increase since 1998 and APR for 1970-1999)--total farmed shrimp 0.009 MMT to 1.1 MMT, 5.2% & 18.8%; total captured shrimp 1.08 MMT to 2.9 MMT, 5.5% & 3.6%; total landed farmed and captured shrimp 1.09 MMT to 4.02 MMT, 5.4 & 4.8% (Source: FAO, 2001a)

Shrimp farming is currently practiced in over 50 countries worldwide, and the sector has grown at an annual average of over 18.8% since 1970 (FAO 2001a). By contrast, the total catch of shrimp from capture fisheries has grown at a relatively modest rate of 3.8% per year, from just over 1 MMT to just under 3 MMT over the same period. Moreover, although shrimp accounted for only 2.6% of total global aquaculture production by weight in 1999, it represented 12.4% of total aquaculture production by value, at US$ 6.7 billion (FAO 2001a). It is perhaps not surprising therefore that farmed shrimp currently contribute over a quarter of total global shrimp landings (Figure 1), and constitutes the single most valuable internationally traded aquaculture commodity worldwide (FAO 2000). Tables 1 and 2 present statistical information concerning global shrimp aquaculture production by species and by country for 1999 according to FAO (2001a). Figure 2 presents the statistical time series and growth of the shrimp species.

Table 1. Total world production of farmed shrimp in 1999, by weight. Source: FAO (2001a).

Shrimp species	Production (MT)	Change 1998–99 (%)
Giant tiger prawn *Penaeus monodon*	575,842	+3.9
Whiteleg shrimp *Penaeus vannamei*	187,224	-5.6
Fleshy prawn *Penaeus chinensis*	171,972	+19.5
Penaeid shrimp *Penaeus* spp (spp not given)	95,634	+20.2
Banana prawn *Penaeus merguiensis*	53,109	+7.5
Metapenaeid shrimp *Metapenaeus* spp	22,421	+1.0
Blue shrimp *Penaeus stylirostris*	12,390	-22.1
Indian white prawn *Penaeus indicus*	7,043	+13.7
Kuruma prawn *Penaeus japonicus*	2,359	-6.6
Southern white shrimp *Penaeus schmitti*	1,364	-21.3
Natantian decapods *Natantia*	904	+175.0
Akiami paste shrimp *Acetes japonicus*	270	+2.3
Redtail prawn *Penaeus penicillatus*	107	-21.9
Palaemonid shrimp, spp not given	98	-39.9
Total	**1,130,737**	**+5.2**

Table 2. Total world production of farmed shrimp in 1999, by country. Source: FAO (2001a).

Country/Territory	Production (MT)	Change 1998–99 (%)
Thailand	230,000	-9.0
China	170,830	+19.4
Vietnam	131,800	+13.6
Ecuador	119,700	-16.9
Indonesia	119,120	+0.8
India	114,670	+41.4
Bangladesh	81,068	+22.7
Philippines	35,898	-5.0
Mexico	29,120	+22.6
Brazil	16,750	+131.0
Malaysia	12,188	+23.9
Colombia	9,227	+23.6
Honduras	8,000	0
Taiwan, Province of China	6,065	+9.3
Venezuela	6,000	0
Nicaragua	4,198	-12.2
Peru	4,005	-12.5
Sri Lanka	3,820	-41.4
Madagascar	3,486	+39.9
Belize	3,163	+92.6
Panama	2,585	-74.3
Costa Rica	2,465	+5.0
Australia	2,444	+75.4
USA	2,098	+4.9
New Caledonia	1,906	+21.5
Iran	1,800	+107.1
Japan	1,726	-13.4
Guatemala	1,403	+1.6
Cuba	1,364	-21.3
Saudi Arabia	1,300	-23.0
S. Korea	1,142	+35.0
Seychelles	227	-65.0
Guyana	162	+35.0
El Salvador	149	-33.2
Spain	138	-25.4

Country/Territory	Production (MT)	Change 1998–99 (%)
South Africa	120	+34.8
Suriname	105	0
Singapore	82	+24.2
Pakistan	76	+10.1
Cambodia	62	-68.5
Brunei	45	-34.8
Cyprus	43	+72.0
French Polynesia	43	-10.4
Fiji Islands	39	+11.4
Turkey	30	-88.9
Guam	25	+13.6
Italy	18	-28.0
Solomon Islands	13	0
Myanmar	8	0
Albania	5	-37.5
St. Kitts and Nevis	5	+25.0
Bahamas	1	0
Total	**1,130,737**	**+5.2**

These data show that the giant tiger prawn, *Penaeus monodon,* was the major cultivated species in 1999 (575,842 MT or 50.9% of total production; capture fisheries 144,042 MT), followed by the whiteleg shrimp, *P. vannamei* (187,224 MT or 16.5%; capture fisheries 2,479 MT), the fleshy prawn, *P. chinensis* (171,972 MT or 15.2%; capture fisheries 70,725 MT), the banana prawn, *P. merguensis* (53,109 MT or 4.7%; capture fisheries 78,743 MT), metapenaeid shrimp (22,421 MT or 2.0%; capture fisheries 59,493 MT), the blue shrimp, *P. stylirostris* (12,390 MT or 1.1%), the Indian white prawn, *P. indicus* (7,043 MT or 0.6%), the Kuruma prawn, *P. japonicus* (2,359 MT or 0.2%), and the Southern white shrimp, *P. schmitti* (1,364 MT or 0.1% of total reported farmed shrimp production). In marked contrast, the main landed shrimp species from capture fisheries in 1999 were the Akiami paste shrimp, *Acetes japonicus* (598,602 MT or 20.7% of total catch), Natantian decapods (532,850 MT or 18.4%), the Southern rough shrimp, *Trachypenaeus curvirostris* (403,027 MT or 13.9%), and the Northern prawn, *Pandalus borealis* (338,969 MT or 11.7%); (FAO, 2001a). Clearly, that aquaculture contributed 28% of total shrimp landings is true (Figure 1), but obviously the shrimp species composition is different and therefore not strictly comparable.

Shrimp aquaculture production is currently almost totally restricted to developing countries (1,124,188 MT or 99.4% of total production); it is especially concentrated in the Asian region (911,773 MT or 80.6%; mainly Thailand, China, Vietnam, Indonesia, India, Bangladesh, Philippines, and Malaysia). The Latin America and Caribbean region also produce significant amounts (208,402 MT or 18.4%; mainly Ecuador, Mexico, Brazil, Colombia, Honduras, Venezeula, Nicaragua, Peru, Belize, and Panama). Remaining regions produce small amounts: Oceania (4,470 MT or 0.4%; mainly Australia and New Caledonia), Africa (3,833 MT or 0.3%; mainly Madagascar and South Africa), North America (USA: +2,098 MT or 0.18%), and lastly Europe (161 MT; mainly Spain and Italy) (Table 2, FAO, 2001a).

By comparison, only 80.6% of wild-caught shrimp were landed by developing countries (2.33 MMT in 1999), with the remaining 0.56 MMT landed by developed countries. There were also marked regional differences; the Asian region had the highest shrimp catch (1.98 MMT or 68.6%; main countries China [1.05 MMT or 36.3% of world shrimp capture fisheries landings], Indonesia, India, Malaysia, Thailand, and Vietnam), followed by North America (258,081 MT or 8.9%; main countries USA and Canada), Europe (248,199 MT or 8.6%; main countries Greenland, Norway, and Iceland), Latin America and the Caribbean (189,045 MT or 6.5%; main countries Mexico, Brazil, Argentina, and Panama), Africa (100,789 MT or 3.5%; main countries Nigeria, Madagascar, and Mozambique), and Oceania (27,525 MT or 0.95%; main country Australia) (FAO, 2001a). Despite the above rosy picture of the emerging shrimp farming industry, the sector has been facing some severe difficulties and constraints evidenced by decreasing growth over the last decade (Figure 2).

About half the producer countries posted either no growth or actual declines from 1998 to 1999, including Thailand and Ecuador (Table 2). For example, whereas farmed shrimp production increased at an average rate of between 30–40% per year during the blue revolution of the 1970s and 1980s (31.6%, 41.7%, 33.8%, 42.7% per year for the periods 1970–1974, 1975–1979, 1980–1984, 1985–1989, respectively), the growth of the sector has decreased to 5–10% per year in the 1990s (9.8% and 5.9% for the periods 1990–1994 and 1995–1999, respectively). To a large extent decreasing growth has resulted from constraints faced by the sector: disease outbreaks and deteriorating environmental conditions (ADB/NACA 1998; Boyd and Clay 1999; Chamberlain 1997; FAO 1998, 1999; Fast and Menasveta 2000; Fegan, 2001; Phillips 1995).

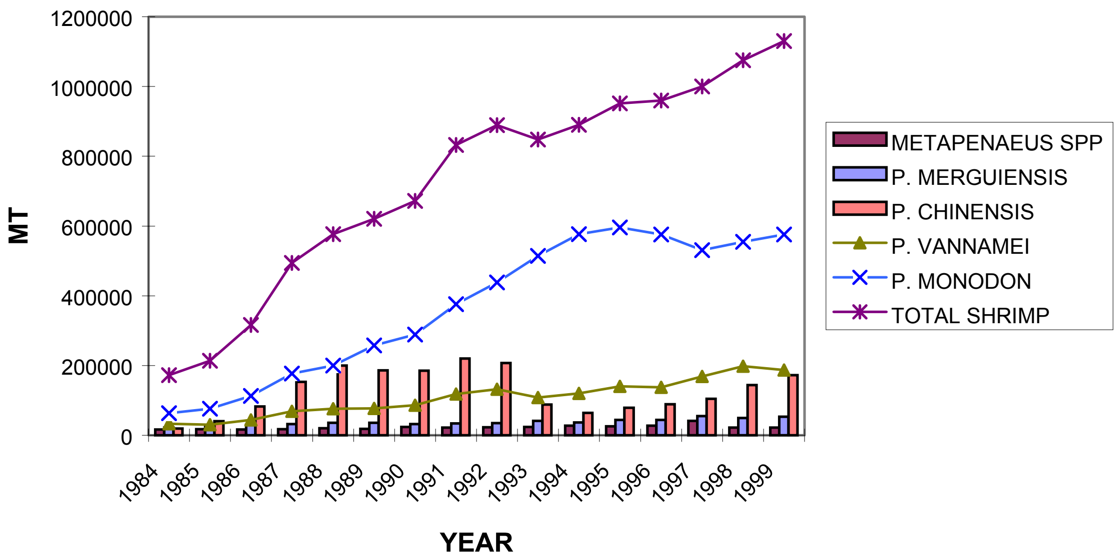


Figure 2. Global shrimp aquaculture production (Total and for main species) Growth (expressed as % increase since 1998 and APR for 1984-1999): *P. monodon* 63,692 to 575,842 MT, 3.9% & 18.4%; *P. vannamei* 33,092 to 187,224 MT, -5.6% & 13.2%; *P. chinensis* 19,375 to 171,972 MT, 19.5% & 16.9%; *P. merguiensis* 22,219 to 53,109 MT, 7.5% & 6.4%; *Metapenaeus* spp 16,252 to 22,421 MT, 1.0% & 2.3%; total shrimp 172,292 to 1,130,737 MT, 5.2% & 14.4% (Source: FAO, 2001a).

The aim of this paper is to undertake a review of feeds and feed management practice in shrimp aquaculture, and specifically to:

- Assess the environmental implications and trends of feed use in shrimp aquaculture, particularly the use of fishmeal and water pollution caused by feeds.
- Identify practices (at farm, manufacturing and ecosystem levels that can reduce environmental impacts associated with the use of shrimp aquafeeds, giving special attention to fish meal and effluent management, and practical measures that can promote efficient use of feed resources.
- Analyze the constraints and opportunities for promoting such practices, including costs and benefits for their adoption.
- Identify follow up activities to support efficient use of feed resources, including nutrition and feed management research, information exchanges, and others as appropriate.

In addition to the above, the review was asked to address the following issues:

- Assertions that shrimp aquaculture is literally “feeding on world fisheries” and that the production of shrimp contributes to net loss of wild caught fish.
- Trends in the use of alternative ingredients as fish meal replacers, including soybean meal, and other agricultural byproducts.
- Short and long-term strategies for improving the efficiency of feed resource use in shrimp aquaculture.
- Provide a comprehensive set of references for further reading on the subject.

Farming Systems and Feeding Methods

The farming systems currently employed can be broadly divided into three basic categories: extensive, semi-intensive, and intensive farming systems. Although the precise definitions of these systems vary from country to country, farmer to farmer, and author to author, the following generalizations can be made about the operating characteristics of these farming systems (Fast and Menasveta 2000; Rosenberry 2000; Wyban and Sweeney 1991).

Extensive Farming Systems (EFS)
Usually these systems use large earthen ponds (ranging in size from a few hectares to as much as 100 ha); employ low water exchange (tidal or pump, 0–5% water exchange/day); have low stocking densities (usually below 5 shrimp/m^2); and provide no artificial aeration, little or no fertilization or supplementary feeding, low labor inputs (less than 0.1 workers/ha), and low production costs (US $1–3/kg live shrimp). These farms tend to produce low shrimp yields (under 1,000 kg shrimp [head-on]/ha/year).

Examples of shrimp-producing countries employing EFS include Vietnam (40–85% of all farms depending on the source), India (75–85%), Indonesia (50–60%), Ecuador (40%), China (30%), Malaysia, Philippines (30%), and Nicaragua (25%) (Rosenberry 1999). Other countries in Asia that use the extensive farming method include Bangladesh, Cambodia, Myanmar, , Indonesia (ADB/NACA 1998) and India (Kutty 1995).

Semi-Intensive Farming Systems (SIFS).
These farms usually use small to moderate-sized earthen ponds (<1–20 ha in size), with moderate water exchange (pumping: 5–20% water exchange/day), intermediate shrimp stocking densities (5–25 shrimp/m^2), partial or continuous aeration (particularly during the final phase of production), fertilization and/or supplementary/ complete feeding, moderate labor inputs (0.1–0.5 workers/ha). Semi-intensive farms produce moderate shrimp yields (1,000–5,000 kg shrimp/ha/year), and have moderate production costs (US $2–6/kg live shrimp).

Shrimp producing countries employing SIFS include Venezuela, Iran and New Caledonia (100% of all farms in each), USA (95%), Panama (90%), Brazil (85%), Nicaragua (75%), Thailand (10–70%), China (65%), Philippines, Malaysia, Australia (60%), Taiwan Province of China (50%), Ecuador (55%), Indonesia (25–30%), and India (20%), Vietnam (45%), Bangladesh, Cambodia, Sri Lanka, Honduras, and Mexico (Rosenberry 1999; Chingchai Lohawatanakul/Chen Ming Dang 2001; ADB/NACA 1998; Corrales et al. 1998; Kutty 1995; Akiyama 1993; Chamberlain 1991; Clifford 2000).

Intensive Farming Systems (IFS).
This method is usually practiced in small lined earthen ponds, raceways, or tanks (0.1–2 ha), typically with high water exchange rates (pumping: 25–100% water exchange/day) although not in closed systems, high shrimp stocking densities (above 25 shrimp/m^2), partial or continuous aeration (particularly during the final phase of production), fertilization and/or complete feeding, high labor inputs (1–3 workers/ha).

The intensive method often produces high shrimp yields (above 5,000 kg shrimp/ha/year), and has generally high production costs (US $4–8/kg live shrimp).

Examples of shrimp producing countries employing IFS include: Asian region - China, India, Indonesia, South Korea, Malaysia, Philippines, Sri Lanka, Taiwan Province of China, Thailand (ADB/NACA 1998); Belize (McIntosh 1999a, 1999b, 2000a, 2000b, 2001a; McIntosh and Carpenter 1999; Rosenberry 1999, 2000), Brazil (Nunes and Suresh 2001a), Mexico (Rosenberry 2000; Clifford 2000; Monroy and Peterson 2001)),; Indonesia (Chamberlain 1991), Japan (Liao and Chien 1994; Shigeno 2001), Panama (Grillo et al. 2000), Thailand (Chanratchakool et al. 1995); ; USA (Browdy et al. 2001; Fast and Menasveta 2000; Kim 2000; Moss et al. 2001a, 2001b; Samocha et al. 2001a; Tacon et al. 2001a; Treece 2000; Treece and Hamper, 2000; Wyban and Sweeney, 1991). According to Rosenberry (1999) the reported percentage of farms employing IFS were as follows: Taiwan Province of China 50%, Australia 40%, Thailand, Indonesia 25%, Brazil 15%, Malaysia 10%, China, Ecuador, India, USA 5%. By contrast, recent industry estimates report IFS within key Asian countries as Thailand 90% of all farms, China 40%, Vietnam 15%, Indonesia 10%, India 5% (data according to Dr. Chingchai Lohawatanakul/Dr. Chen Ming Dang, Charoen Pokphand Foods Public Company Ltd – personal communication, June 2001).

Table 3 shows the estimated production characteristics of the main shrimp-producing countries according to the most recent complete statistical report by Rosenberry (1999). Little or no officially approved data exist, and Rosenberry’s country production estimates are considerably lower than those reported by countries to FAO (Table 2). Nevertheless, Rosenberry has estimated that the majority of the world’s 375,913 shrimp farms in 1999 used EFS (54%), followed by SIFS (28%) and IFS (18%). These estimates are similar to those by ADB/NACA (1998), which surveyed over 4,802 shrimp farms in Asia and reported EFS used in 60% of farms (based on a definition of <10 shrimp/m^2 stocking density), SIFS 23% (5–30 shrimp/m^2 stocking density) and IFS 17% (> 30 shrimp/m^2 stocking density).

Table 3. Production characteristics of the major shrimp-producing countries in 1999 Source: Rosenberry 1999).

Country (# farms)[1]	Production (MT)[2]	Ha in production[3]	Production Kg/ha
Thailand (20,000)	200,000	80,000	2,500
China (10,000)	110,000	180,000	611
Indonesia (225,000)	100,000	350,000	286
Ecuador (1,200)	85,000	100,000	850
India (100,000)	70,000	130,000	538
Philippines (4,000)	40,000	60,000	667
Vietnam (6,000)	40,000	200,000	200
Taiwan Province of China (3,000)	20,000	5,000	4,000
Brazil (110)	15,000	6,000	2,500
Malaysia (800)	6,000	4,000	1,500
Nicaragua (130)	4,000	6,000	667
Venezuela (12)	4,000	2,000	2,000
Iran (150)	2,500	4,000	625
Australia (45)	2,400	600	4,000
Panama (35)	2,000	3,000	667
New Caledonia (11)	1,850	450	4,111
USA (20)	1,500	400	3,750

[1]Number of farms reported. [2]Head-on production in MT. [3]Reported ha in production.

As with all animal production systems, the growth and production of farmed shrimp is largely dependent upon the supply and intake of dietary nutrient inputs and feeds. The latter usually represent the largest single operating cost of most semi-intensive and intensive shrimp farming operations (ADB/NACA 1998; Akiyama and Chwang 1989; Ma Shen 1997). For example, Ling, Leung and Shang (1997) reported that feed costs represented 23–56% of total farm production costs for semi-intensive shrimp farming systems within the Asian region, followed by seed cost (10–22%).

In general, the feeding methods employed by shrimp farmers consist of the following.

- **No fertilizer or feed application** is typical of traditional extensive farming systems, in which shrimp growth and production depends on the consumption of food organisms naturally present in the pond ecosystem and influent water (Fast and Menasveta 2000; Rosenberry 2000).

- **Fertilizer application** is similar to the method above but applies chemical fertilizers and/or organic manures to stimulate and enhance the natural productivity of the pond ecosystem, thus increasing natural food production and availability for the cultured shrimp (ADB/NACA 1998; Clifford 1992; Fast and Menasveta 2000; Kutty 1995; New et al. 1995; Rosenberry 2000; Treece 2000).

- **Fertilizer and/or supplementary feed application** is usually used in semi-intensive farming systems, in which shrimp growth relies on the co-feeding of endogenously supplied local food organisms (whose production is usually enhanced by applying fertilizers) and exogenously supplied supplementary feeds. The latter feeds may be simple farm-made moist/dry aquafeeds or industrially formulated commercial aquafeeds (ADB/NACA 1998; Ahamad Ali 1995; Akiyama 1993; Athanasiadis 2001; Boonyaratpalin and New 1995; Chamberlain 1992; Clifford 1992, 2000; Cook and Clifford 1997a, 1997b, 1998; Cruz, 1991; Fast and Menasveta 2000; Kutty 1995; New et al. 1995; Reddy 1994; Rosenberry 2000; Ma Shen 1997; Treece 2000).

- **Fertilizer and/or complete feed application** are typical of intensive farming systems, where shrimp growth is almost totally dependent upon the external provision of a nutritionally complete diet for the entire culture period. These feeds generally consist of formulated commercial aquafeed or, to a lesser extent, farm-made aquafeed or fresh items such as trash fish (ADB/NACA 1998; Ahamad Ali 1995; Athanasiadis 2001; Boonyaratpalin and New 1995; Chanratchakool et al. 1995; Clifford 1992, 2000; Jackson 2000; Jory 1995a; Kutty 1995; Ma Shen 1997; McIntosh 2000a; New et al. 1995; Reddy 1994; Nunes 2000a, 2001a; Rosenberry 2000; Shigeno 2001; Treece 2000; Wyban and Sweeney 1991).

The choice of feeding method largely depends on the intended farming system and shrimp stocking density (and the resulting availability of food per stocked animal), the financial resources and other inputs available to the farmer, and the market value of the cultured species. At one end of a spectrum are low-cost extensive/semi-intensive farms using fertilization and supplementary feeding generally with farm-made aquafeeds derived from locally available resources. At the other end, large-scale commercial farming operations use intensive methods with fertilization and feeding, usually using industrially compounded aquafeeds. Farm-made aquafeeds are defined here as "feeds in pellet or other forms, consisting of one or more artificial and/or natural feedstuffs, produced for the exclusive use of a particular farming activity, not for commercial sale or profit" (New et al. 1995).

Global Shrimp Aquafeed Production

No statistical information currently exists on total global production of farm-made aquafeeds used for shrimp feeding (New 1998; New et al. 1995). The use of farm-made aquafeeds is usually restricted to resource-poor farmers in Asia (ADB/NACA 1998), and farm-made aquafeeds will in all likelihood be gradually replaced by commercial aquafeeds (Tacon 2000a). Another more urgent and recent incentive for this shift away from farm-made aquafeeds to industrially prepared feeds is the need to avoid introducing viable disease organisms from unprocessed marine food organisms (including trash fish, crustaceans, and molluscs) used for farm-made aquafeeds (ADB/NACA 1998; Fegan 2001; Gill 2000a; Prior et al. 2001; Rodrigues et al. 2001; Tacon and Forster 2000).

Although over half the shrimp farms in the world are reportedly operated extensively (Rosenberry 1999), an estimated 75% to 80% of all farmed shrimp are grown with industrially compounded aquafeeds in one form or another (IFOMA 2000; Tacon and Forster 2000). Using the total global shrimp farm production figure of 1.13 MMT in 1999 (FAO 2001a), and global average shrimp feed conversion ratio (FCR) of 2.0 (i.e., it takes 2 MT of dry aquafeed to produce 1 MT of shrimp on a live-weight basis (Tacon et al. 1998) we can estimate total global production of compounded aquafeeds for shrimp in 1999 at roughly 1.70 to 1.81 MMT (assuming 75% and 80% feed usage, respectively).

These figures approximate the estimated annual shrimp aquafeed volumes reported for the major shrimp-producing countries during 1999 and 2000 (Table 4).

Table 4. Estimated shrimp aquafeed market volumes reported for the major shrimp producing countries during the period 1999-2000.

Country	Production—1999 (MMT)[3]	Production—2000 (MMT)
Thailand	440[1]	486[2]
China	132[1]	276[2]
Vietnam	30[1]-120	225[2]
India	120	180[2]
Indonesia	90[1]	152[2]
Ecuador	150[3]	105[3]
Bangladesh	50	75
Taiwan Province of China	41[4]-45[1]	50
Mexico	65[3]	46[3]
Brazil	15[3]	35[3]
Philippines	6[1]-20	30
Honduras	29[3]	27[3]
Malaysia	17[4]	25
Colombia	21[3]	18[3]
Belize	7	12
Madagascar	6	10
Nicaragua	10[3]	8[3]
Venezuela	7[3]	8[3]
Peru	12[3]	8[3]
Sri Lanka	7	8
Australia	5[1]	7
Iran	4	6
New Caledonia	4	5
Saudi Arabia	3	5
S. Korea	7[4]	4
Japan	5[1]	4
Costa Rica	4	3
USA	4	3
Guatemala	3[3]	2[3]
Panama	3[3]	2[3]
Cuba	3	2
Others	3	5
Total Global	**1,406**	**1,832**

[1]Akiyama and Hunter (2000). [2]Dr. Lohawatanakul/Dr. Chen Ming Dang, personal communication, June 2001. [3]Dr. Victor Suresh, personal communication, May 2001. [4]Merican (2000).

The total estimated shrimp feed sold was 1.41 MMT for 1999 and 1.83 MMT for 2000. Of particular note were decreased sales reported in most countries in Latin America and the Caribbean region (Table 4).

Severe shrimp losses from disease outbreaks reduced demand for feed there (Calderon 2001; Rodrigues et al. 2001). Assuming an average retail feed price of $0.50–1.25/kg (the range reflects generally lower Latin American and higher Asian feed prices), the current value of total shrimp aquafeed sales in 1999 is estimated at between $1.25–1.50 billion. In general, the higher costs of Asian shrimp feeds stems from their higher nutrient content compared with Latin American shrimp feeds (Table 5).

Table 5. Mean nutrient content of commercial shrimp feeds in Asia and the Americas.
Note: all values expressed as % by weight, as fed basis.

Country	W[1]	CP[2]	Ash	Fat	St[3]	TE[4]	Ca[5]	P[6]	Ca/P
Brazil (1)	7.8	38.4	11.2	6.9	20.7	3661	2.30	1.51	1.52
Colombia (5)	9.9	31.0	8.8	9.7	27.9	3830	2.57	1.45	1.55
Ecuador (3)	ND	28.7	9.8	5.5	34.7	3692	2.15	1.12	1.95
Peru (1)	10.1	34.2	6.8	6.8	36.5	4067	1.23	1.02	1.21
Mexico (3)	8.5	38.3	9.9	8.5	25.0	3988	2.27	1.55	1.47
USA (4)	9.4	42.3	11.0	9.9	14.4	4022	2.27	1.65	1.36
India (5)	ND	40.4	14.6	9.3	12.0	3662	2.39	0.98	2.44
Indonesia (2)	10.4	40.5	10.3	7.3	21.7	3961	2.03	1.52	1.30
Japan (1)	ND	53.0	19.6	10.0	5.0	4137	ND	ND	ND
New Caledonia (2)	9.2	40.2	11.0	6.2	23.3	3782	1.97	1.75	1.13
Philippines (2)	7.2	41.2	10.2	7.6	20.6	3973	2.10	1.70	1.23
Taiwan Province of China (1)	7.9	43.3	8.8	7.9	22.2	4141	ND	ND	ND
Thailand (7)	8.9	41.5	12.4	7.5	20.6	3873	2.34	1.47	1.43
Singapore (1)	10.5	40.6	8.6	6.2	27.0	3989	1.05	1.39	0.76

[1] Moisture, [2] Crude Protein, [3] Starch, [4] Total Energy (Kcal/kg of shrimp produced), [5]Calcium and [6]Phosphorus.
ND = Not determined. Source: Devresse (1995).

The higher protein content used in Asian diets fits with the more carnivorous feeding habits of the main shrimp species cultured (*P. monodon* and to a lesser extent *P. chinensis* in Asia compared with *P. vannamei* and secondarily *P. stylirostris* in the Americas). Moreover, carnivorous shrimp species are less able to harness the natural pond biota (including suspended particulate matter) than their more omnivorous or detritivorous counterparts (Tacon and Akiyama 1997). Although no precise information exists concerning the dietary protein requirements of different shrimp species of the same size and reared under the same culture/dietary conditions, the minimum reported dietary protein requirements of various shrimp species have been summarized by Lim and Akiyama (1995) and Guillaume (1997) as follows:

- *Penaeus japonicus* 40-60%
- *Penaeus brasiliensis* 45-55%
- *Penaeus monodon* 35-50%
- *Penaeus aztecus* 29-51%
- *Penaeus merguiensis* 34-50%
- *Penaeus indicus* 40-43%
- *Penaeus setiferus* 28-32%
- *Penaeus stylirostris* 30-35%
- *Penaeus penicillatus* 22-27%
- *Metapenaeus monoceros* 55%
- *Penaeus cailorniensis* >44%
- *Penaeus kerathurus* >40%
- *Penaeus vannamei* >30%
- *Penaeus duorarum* 30%
- *Metapenaeus macleayi* 27%

Conservative projections for global compound shrimp aquafeed indicate that production could reach 2.0 MMT by 2000, 2.3 MMT by 2005, and 2.5 MMT by 2010 (Table 6).

Table 6. Estimated and projected global shrimp and finfish aquafeed production: 1999–2010.

Species	1999	2000	2005	2010
Total shrimp production (MT)[1]	1,130,737	1,228,060	1,494,122	1,732,096
IFOMA (2000) (MT)[2]	–	1,034,000	–	1,684,000
Growth (APR, %/year)[3]	5	4	3	–
IFOMA (2000) (APR, %/yr)[4]	–	5	–	5
Percent on feeds (%)[5]	80	82	87	92
IFOMA (2000) (% on feeds)[6]	–	80	–	90
Species Economic FCR[7]	2.0	2.0	1.8	1.6
IFOMA (2000) FCR[8]	–	1.8	–	1.6
Total aquafeeds used (MT)[9]	1,809,179	2,014,018	2,339,795	2,549,645
IFOMA (2000) estimate[10]	–	1,489,000	–	2,425,000

[1]Total reported FAO farmed shrimp production for 1999, and projections for 2000 to 2010. [2]Total farmed shrimp production projected by to IFOMA (2000). [3] Estimated annual percentage of growth of farmed shrimp production (APR, %). [4] Estimated APR according to IFOMA (2000). [5] Estimated percent of total shrimp production on aquafeeds. [6] Estimated percent of shrimp production on aquafeeds according to IFOMA (2000). [7] Estimated average species group food conversion ratio (total feed used/total shrimp biomass increase). [8] Estimated average species group economic food conversion ratio (total feed used/total shrimp biomass increase) according to IFOMA (2000). [9] Estimated total shrimp aquafeed used (total shrimp production x FCR). [10] Estimated total shrimp aquafeed used according to IFOMA (2000).

These estimates compare favorably with projections by the International Fish meal and Fish Oil Manufacturers Association (IFOMA 2000), which estimated global production would increase from 1.5 MMT in 2000 to 2.4 MMT by 2010 (Table 6). The global production of all types of commercial aquafeeds was estimated at about 13.4 MMT in 1999. By far the largest consumers of such aquafeeds in 1999 were non-filter-feeding carp species (including grass carp, common carp, crucian carp, rohu, mirgal carp, white amur bream, mud carp), followed by marine shrimp, salmonids, marine finfish, tilapia, catfish, eel and milkfish (Figure 3).

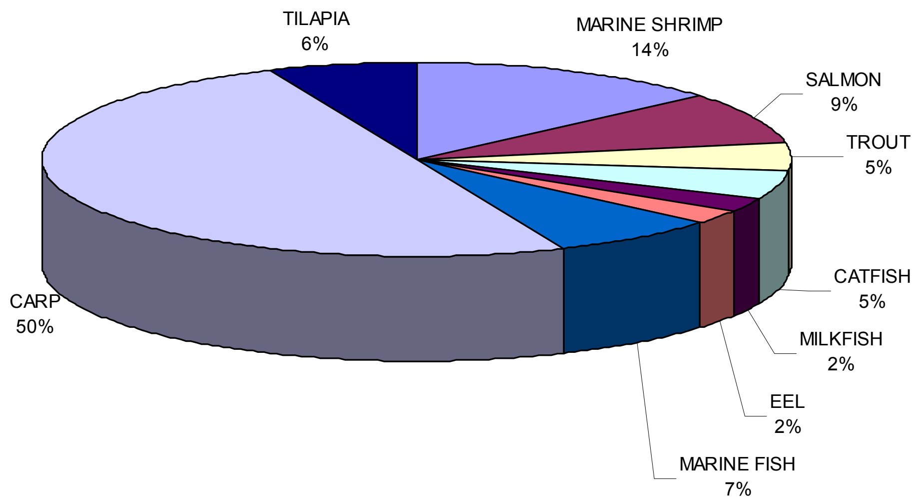


Figure 3. Estimated global compound aquafeed production by species in 1999. Total aquafeed production 13.37 MMT. Carp 6.68 MMT, Marine Shrimp 1.81 MMT, Salmonider 1.17 MMT, Marine Finfish 0.98 MMT, Tilapia 0.86 MMT, Catfish 0.65 MMT, Eel 0.32 MMT and Milkfish 0.29 MMT.

Major Challenges Facing Shrimp Feeds and Feeding Methods

Challenge 1

- Shrimp farmers may lack understanding of the major nutritional role played by natural food organisms (including microorganisms) in the overall diet of shrimp raised under practical farming conditions. The consequent need to consider shrimp feeds and feeding more holistically in the context of the intended farming system and aquatic ecosystem may not be met.

Although the growth and health of all shrimp depends upon the intake of food containing 40 or so essential nutrients, the form in which these nutrients are supplied varies by farming system and feeding strategy employed. For example, with EFS these nutrients are supplied mainly by live food organisms produced within the pond ecosystem, with SIFS they are usually supplied by a combination of natural food organisms and externally supplied supplementary feed inputs, and with IFS these nutrients are usually supplied almost entirely by a nutritionally complete compound aquafeed, either alone or combined with a natural food item of high nutrient value such as whole fish, brine shrimp, bloodworms, or clams.

Simple as these different nutrient pathways appear, the majority of nutritionists and feed manufacturers focus exclusively on the formulation, manufacture, and application of nutritionally complete artificial diets or aquafeeds, irrespective of the proposed farming system and shrimp stocking density. However, Table 7 summarizes findings of major studies that have clearly demonstrated the role played by natural food organisms in the nutritional budget of shrimp fed compound aquafeeds in earthen pond (and to a lesser extent in tank-based) farming systems. The research shows that natural food organisms play a major role in the overall nutritional budget of pond-reared shrimp, even at high stocking densities.

In general, the contribution of natural food organisms to outdoor pond/tank-raised shrimp will depend upon a variety of factors, including 1) the natural feeding habits of the shrimp species, 2) shrimp stocking density and standing crop, 3) pond/tank physical characteristics and preparation/history, 4) climatic conditions, 5) water quality and its management, 6) pond fertilizer and/or feed input, and 7) consequent natural pond productivity and food availability. It follows that the contribution of natural pond biota will be highest at low stocking densities and at the start of the production cycle, when the total shrimp biomass or standing crop is lowest. The subsequent availability and relative contribution of natural pond biota thereafter decreases over the course of the production cycle, with increasing crustacean size and standing crop (for review, see Allan and Maguire 1992; Focken et al. 1998; Gautier et al. 2001; Hunter 1996; Hunter et al. 1987; Lawrence and Lee 1997; Moriarty 1997a; Nunes and Parsons 2000; Palacios et al. 1994; Villamar 1999).

For example, according to Cook and Clifford (1997a) a typical well-managed shrimp farm with nutrient-rich water and abundant benthic polychaete populations should be able to support good growth at a shrimp biomass of 250 kg/ha or more. These authors have recommended the following general feed management guidelines (which account for available natural food organisms within semi-intensive pond farming systems).

1. Initially: No feeding until a critical shrimp biomass of approximately 200 kg/ha is attained;
2. Preliminary feeding: From the time supplemental feed is first supplied until the shrimp biomass reaches about 800 kg/ha, a 25% protein feed of medium quality should be supplied;
3. Intermediate feeding: Once the shrimp biomass exceeds 800 kg/ha, a medium-quality 35% protein feed should be used, and
4. Final feeding: After the estimated biomass of shrimp exceeds 1,200 kg/ha, a 35% protein feed of the highest quality available should be used (Cook and Clifford 1997a).

However, it should also be stated that the practical application of these guidelines would depend upon location (no two ponds are alike), soil conditions and water nutrient availability (the later depending upon the use or not of inorganic and/or organic fertilizers), and the need to closely monitor shrimp biomass within ponds through periodic monitoring.

Challenge 2

- The dietary nutrient requirements of shrimp under practical farming conditions, particularly in outdoor ponds, are not well understood. Aquafeeds and feeding strategies tailored to the farming system need to be developed in order to reduce feed costs and avoid unnecessary nutrient input, feed wastage, and environmental pollution.

At present, little or no information exists about the dietary nutrient requirements of farmed shrimp in ponds; the majority of studies to date have observed shrimp growth in controlled indoor laboratory tanks (Boonyaratpalin 1996; D'Abramo et al. 1997; Kanazawa 1995; O'Keefe 1998; Reddy et al. 1999; Shiau 1998; Teshima et al. 1993; Wang and Liang 2001). Whilst the information generated from laboratory-based feeding trials may be useful in formulating nutritionally complete larval feeds in indoor crustacean hatcheries, or grow-out/broodstock feeds for use in intensive clear-water farming systems, this information cannot be directly applied to outdoor green-water culture conditions typical of EFS, SIFS, and IFS. Shrimp (depending upon the species) also derive a substantial portion of their dietary nutrient needs from naturally available food organisms (Table 7).

Table 7. Summary of major studies that show the importance of natural food organisms in the nutritional budget of pond-raised shrimp.

- **Anderson et al. (1987)** reported that natural pond biota accounted for 53–77% of the growth carbon of pond reared-shrimp (*P. vannamei;* stocking density 20/m^2), compared with 23–47% supplied by an exogenously supplied pelleted shrimp diet.
- **Cam et al. (1991)** reported that natural productivity accounted for 86.7, 42.7, 41.7 and 34.4% of the growth carbon of pond reared shrimp (*P. japonicus;* stocking density 20/m^2 PL_{20-22}: 25mg initial body weight) after 30, 60, 90 and 120 days, respectively. All cultured shrimp were fed a 57.4% protein pellet from day 15 after stocking until the end of the 120-day experiment.
- **Leber and Pruder (1988), Moss et al. (1992) and Moss (1995)** discussed the growth-enhancing effect of unfiltered shrimp pond water on laboratory-reared shrimp (*P. vannamei).* The shrimp reared in plastic-lined microcosm tanks receiving flow-through pond water and fed artificial diets grew over 50% faster than comparable animals receiving clear well water and fed identical diets.
- **Bostock (1991)** reported no difference in the growth of pond-reared shrimp (*P. monodon*; stocking density 10/m^2) in India fed a high-nutrient pelleted diet or a locally produced dough-ball costing 1/3 as much.
- **Teichert-Coddington et al. (1991)** reported that chicken litter (applied at a rate of 220 kg/ha/week) could profitably substitute for high-cost pelleted shrimp feeds (26% crude protein diet) during the first 8–9 weeks of the pond grow-out phase with *P. vannamei/P. stylirostris* (stocking ratio of 89/11 and density 5/m^2).
- **Castille and Lawrence (1989)** found that dietary vitamin fortification was not essential for shrimp (*P. vannamei*) reared in experimental outdoor pens (situated in earthen ponds; initial and final shrimp biomass were 103 and 247g/m^2, respectively).
- **Trino et al. (1992)** reported that dietary vitamin fortification was not essential for shrimp (*P. monodon*; stocking density 5 juveniles/m^2, initial body weight 0.1–0.17g) reared in outdoor ponds. Shrimp were fed a diet containing 34% crude protein and 8% lipid over a 135-day trial period.
- **Cruz-Suarez, Ricque and Aquacop (1992)** reported that pond pen-reared shrimp (*P. monodon*) grew 70–80% faster and had a better food conversion ratio (FCR of 2.2 for the reference diet and 1.7 for a 10% squid meal-supplemented diet). The respective data for shrimp reared in tanks: FCR of 3.4 for the reference diet and 2.8 for the squid meal diet.
- **Akiyama (1993)** reported that feed ingredient costs could be reduced by 30–45% for shrimp (*P. monodon*; stocking density 10–19/m^2) reared in semi-extensive ponds by reducing dietary protein levels (to a minimum of 30% crude protein) and reducing dietary phosphorus and vitamin levels with no loss in growth or shrimp performance; shrimp production and FCR averaged 2.1 MT/ha/cycle and 1.55 at a stocking density of 10/m^2 and 3.5 MT/ha/cycle and 1.59 at a stocking density of 15/m^2, respectively.
- **Trino and Sarroza (1995)** found no difference in the growth or survival rates or apparent food conversion efficiency of shrimp (*P. monodon*; stocking density 7.5/m^2, initial body weight 6 mg) reared in a modified extensive pond-based culture system and fed a high-quality shrimp pellet (40–42% crude protein, 7–9% lipid) with or without a dietary vitamin/mineral premix over a 120-day rearing cycle. The vitamin and mineral supplements represented 20–30% of total shrimp feed ingredient costs.
- **Teichert-Coddington and Rodriguez (1995)** found no difference in the growth, survival rates, or yield of shrimp (*P. vannamei*; stocking density 5 to 11/m^2, initial body weight 0.3 to 1.9 g) reared in earthen ponds that were fed either a 20% or 40% crude protein shrimp pellet.
- **Hopkins, Sandifer and Browdy (1995)** reported no difference in the growth rates of shrimp (*P. vannamei*; stocking density 39 to 78/m^2) reared in plastic-lined ponds with a sandy soil substrate and zero water exchange that were fed either a 20% or 40% crude protein shrimp pellet.
- **Nunes et al. (1997)** reported that natural pond biota accounted for about 75% of the growth carbon of pond-reared shrimp (*P. subtilis*; stocking density 10/m^2) fed a 41.1% crude protein shrimp pellet over a 60-day trial period.
- **Velasco and Lawrence (2000a)** reported no difference in the growth or survival rates of shrimp (*P. vannamei*, stocking density 1.5 (PL/liter) reared in indoor laboratory tanks with zero water exchange and fed a diet with or without a vitamin premix. Interestingly, similar studies with *P. stylirostris* (stocking density 0.75 PL/liter) showed it to be less efficient than *P. vannamei* in utilization of naturally available bacteria as a source of dietary vitamins, evidenced by the reduced survival of animals fed a vitamin-deficient diet.
- **Tacon (1999), Tacon et al. (2000, 2001b)** found no difference in the growth or survival rates of shrimp (*P. vannamei*, stocking density 50/m^2, initial body weight 1g) reared in indoor aquaria receiving unfiltered shrimp pond water or in outdoor experimental zero-water-exchange culture systems that were fed a 35% crude protein shrimp pellet with or without a complete vitamin/trace mineral premix.
- **Otoshi et al. (2001)** reported the growth-enhancing effect of unfiltered shrimp pond water on laboratory-reared shrimp (*P. vannamei*; stocking density 350 10-day PL/230-L tank). Animals receiving flow-through pond water and fed artificial diets grew over 89% faster than comparable animals receiving clear well water and fed identical diets over a 6-week period (final body weight, 1.85g and 0.98g, respectively).

Unfortunately, in the absence of published information on the nutrient requirements of shrimp in pond-based farming systems, almost all of the commercial aquafeeds used in the three types of farming systems are usually over formulated and meet a standard of providing nutritionally complete diets. The aquafeed manufacturers seem to ignore the role played by different shrimp stocking densities and natural food availability in farm systems (Akiyama 1993; Chamberlain 1992; Lawrence 1996a; Lawrence and Lee 1997; Millamena and Trino 1997; Tacon 1999a; Teichert-Coddington and Rodriguez 1995; Trino and Sarroza 1995; Velasco et al. 2000).

Table 8 a), b) and c) shows some recommended nutrient levels for shrimp, commonly adopted as a template by many commercial shrimp feed manufacturers. These nutrient levels were largely educated guesses at best; furthermore, the recommendations include no adjustment for intended farming density, stocking density, shrimp species, or shrimp size (for vitamins, minerals, and fatty acids).

Table 8 a. Recommended nutrient levels in commercial shrimp feeds.

Shrimp size (g)	Protein (%)	Lipid (%)	Cholesterol (%)
0.0-0.5	45%	7.5%	0.40%
0.5-3.0	40%	6.7%	0.35%
3.0-15	38%	6.3%	0.30%
15-40	36%	6.0%	0.25%

Table 8 b. Recommended amino acids in commercial shrimp feeds.

Amino acid	% of protein	36% CP	38% CP	40% CP	45% CP
Arginine	5.8	2.09	2.20	2.32	2.61
Histidine	2.1	0.76	0.80	0.84	0.95
Isoleucine	3.5	1.26	1.33	1.40	1.58
Leucine	5.4	1.94	2.05	2.16	2.43
Lysine	5.3	1.91	2.01	2.12	2.39
Methionine	2.4	0.86	0.91	0.96	1.08
Methionine+cystine	3.6	1.30	1.37	1.44	1.62
Phenylalanine	4.0	1.44	1.52	1.60	1.80
Phenylalanine+tyrosine	7.1	2.57	2.70	2.84	3.20
Threonine	3.6	1.30	1.37	1.44	1.62
Tryptophan	0.8	0.29	0.30	0.32	0.36
Valine	4.0	1.44	1.52	1.60	1.80

Table 8 c. Recommended vitamin concentrations in commercial shrimp feeds. [1]100 mg/kg, coated heat-stable derivative.

Vitamin	Quantity/kg feed	Mineral	Quantity/kg feed
Thiamin	50 mg/kg	Calcium	2.3%
Riboflavin	40 mg/kg	Phosphorus (available)	0.8%
Pyridoxine	50 mg/kg	Phosphorus (total)	1.5%
Pantothenic acid	75 mg/kg	Magnesium	0.2%
Niacin	200 mg/kg	Sodium	0.6%
Biotin	1 mg/kg	Potassium	0.9%
Inositol	300 mg/kg	Iron	300 ppm
Choline	400 mg/kg	Copper	35 ppm
Folic acid	10 mg/kg	Zinc	110 ppm
Cyanocobalamin	0.1 mg/kg	Manganese	20 ppm
Ascorbic acid[1]	1,000 mg/kg (100)[1]	Selenium	1 ppm
Vitamin A	10,000 IU/kg	Cobalt	10 ppm
Vitamin D	5,000 IU/kg		
Vitamin E	300 mg/kg		
Vitamin K	5 mg/kg		

Fatty acid requirements: 18:2n-6 (0.4% feed), 18:3n-3 (0.3% feed), 20:5n-3 (0.4% feed), 22:6n-3 (0.4% feed)
Source: (Akiyama et al.1991).

In many shrimp-producing countries, nutrient standards for manufactured aquafeeds, including shrimp feeds, are imposed upon the feed industry and farmer by legislation. Such legislative requirements are usually based on an assumption that feeds provide the complete diet with nutrient specifications derived from laboratory-based feeding trials. This approach ignores the intended farming system and shrimp stocking density (Cruz 1997; Djunaidah 1995; New et al. 1995).

Table 9 provides an example, showing nutrient standards for shrimp feeds from the Department of Fisheries in Thailand. Clearly, if farmers are to reduce productions costs and maximize economic benefit from their pond-based farming systems, standards need to be developed under a wider set of conditions and applied judiciously.

Table 9. An example of feed formulation requirements for marine shrimp, issued by Thai Ministry of Fisheries.

Marine shrimp	Protein ≥35–38%	Fat ≥3%	Fiber ≥3%	Moisture ≤12%
Larvae (Z-M)	≥38–52%	≥3–13%	≥0.5–3%	≤6–12%
PL_{1-15}	≥38–50%	≥4–10%	≥2.5–4%	≤10.5–12%
Feed #00	≥38–42%	≥3.5–5%	≥3.0–4%	≤12%
Feed #0	≥36–42%	≥3–5%	≥3.0–4%	≤11–12%
Feed #1	37–40%	4–5%	3.0–4%	<12%
Feed #2	36–40%	4–5%	3.0–4%	<12%
Feed #3	35–38%	4–5%	3.0–6%	<12%

Source: (Corpron and Boonyaratpalin 1999).

It follows that if practical conclusions are to be drawn from nutrient requirement studies and feeding trials, then the experiments must be performed under conditions mimicking, as far as economically possible, those of the intended farm production unit and environment, including production facility, feed preparation technique, feeding method, water quality, photoperiod, and shrimp stocking density (D'Abramo and Castell 1997; Freeman and Duerr 1991; Lawrence and Lee 1997; Tacon 1996). The below points summarizes the major factors to consider when conducting nutrient requirement studies and feeding trials with shrimp:

- Experiments should be conducted under conditions mimicking as far as possible those of the intended farm production unit and environment (i.e., on-farm conditions), including the holding facility (indoor or outdoor tank, pond, pen, or cage), feed preparation technique (grinding, pelleting, drying; diet texture, form, shape, size, buoyancy, and water stability), feeding method (hand, demand, or automatic feeding; feeding frequency and rate (fixed or satiation feeding), water quality (temperature, turbidity, salinity, oxygen, and mineral concentration; water exchange rate, water circulation pattern, and artificial aeration), photoperiod (artificial or natural), and crustacean stocking density.
- During nutrient requirement studies, animals should not be fed on a restricted regime but rather should be fed ad libitum or "to satiation," as a restricted feeding regime introduces competitive interactions and increases disparity in feed acquisition. Moreover, it is essential that experimental animals dictate their own feed intake and nutrient input level.
- The growth performance of experimental animals should be at least equal to that of the target species under practical farming conditions so that dietary nutrient requirements and diet evaluations can be ascertained under conditions of maximum attainable growth. Furthermore, nutrient requirement studies should be of sufficient duration that the animals show a 10-fold increase in body weight.
- Full feed ingredient descriptions, including International Feed Number (IFN), chemical composition, and particle size, should be provided when reporting dietary formulations and the results of nutritional feeding studies.
- Nutrient digestibility studies should ensure that a range of different feed ingredient inclusion levels and ingredient particle sizes be tested, that digestibility measurements be disaggregated on the basis of feed preparation method employed (cold pelleted feeds, conventional steam pelleted feeds, and extrusion pelleted feeds), and that experimental animals be fed to satiation several times per day under similar on-farm ambient conditions. In addition, it is also recommended that research efforts be focused on simple in-vitro digestion techniques that can rapidly estimate nutrient digestibility.
- In the unique case of semi-intensive pond farming systems, it is recommended (in addition to the first recommendation) that a combination of food-web isotope tracer studies and nutrient-balance modeling studies be undertaken to better understand nutrient pond dynamics and study the nutritional contribution of natural food organisms in the overall nutritional budget of pond-reared crustaceans.
- Finally, to ensure the applicability and rapid transfer of research data to farmers, wherever possible, nutrition experiments (based on the use of practical diets) should be conducted in-situ on comparable crustacean farms, and the data generated should be evaluated from an economic viewpoint. An analysis of crustacean quality and tissue histology should also be undertaken on a routine basis during these extended feeding trials whenever possible.

Challenge 3

- The urgent need to turn the shrimp farming sector from a net consumer of fishery resources into a net producer of much needed food-grade aquatic produce.

Use of Capture Fisheries Animal By-products for Aquafeeds

At present the shrimp farming industry is totally dependent upon marine capture fisheries for sourcing its dietary animal protein and lipid inputs. From 25–50% of the ingredients in most commercial shrimp aquafeeds are derived from marine capture fisheries, including fish meal, fish oil, shrimp/crustacean meal, squid meal, krill meal, and other miscellaneous products such as fish solubles, fish silages/hydrolysates, fish/squid liver meals, and seaweed extracts (Civera et al. 1998; Cruz-Suarez et al. 1998; 2000a; Davis 2000; Devresse 1996; Tacon and Barg 1998; Vargas et al. 1998). For example, commercial shrimp feeds for *P. monodon* in Thailand are reported to contain 30–35% fish meal, 5–10% shrimp meal, 5% squid meal/squid liver powder, and 2% fish oil (Corpron and Boonyaratpalin 1999).

If one assumes conservative average global proportions of fish meal and fish oil used in shrimp aquafeeds of 26% and 2% for 1999 (Table 10), the sector consumed an estimated 470,386 MT of fish meal and 36,184 MT of fish oil, or about 21.2% of the total fish meal (Figure 4) and 5.8% of the total fish oil (Figure 5) used in all compound aquafeeds in 1999.

Table 10. Estimated and projected fish meal and fish oil use in shrimp feeds: 1999–2010.

	1999	2000	2005	2010
Total aquafeeds used (MT)[1]	1,809,179	2,014,018	2,339,795	2,549,645
IFOMA (2000) estimate[2]	–	1,489,000	–	2,425,000
Average fish meal content (%)	26	24	14	4
IFOMA (2000) estimate	–	25	–	20
Average fish oil content (%)	2	2	1	1
IFOMA (2000) estimate	–	2	–	3
Total fish meal used (MT)	470,386	483,364	327,571	101,986
IFOMA (2000) estimate	–	372,000	–	485,000
Total fish oil used (MT)	36,184	40,280	23,398	25,497
IFOMA (2000) estimate	–	30,000	–	73,000

[1] Data from Table 6. [2] Projections made by IFOMA (2000).

In view of these high consumption levels, it is perhaps not surprising that the shrimp farming sector is currently consuming more fishery resources than it is producing (by weight). In other words, the sector is currently a net consumer of aquatic products rather than a net producer. For example, the consumption of 470,386 MT of fish meal (dry basis) is equivalent to the use of approximately 2,351,930 MT of fish (wet basis; assumes a pelagics-to-fishmeal conversion factor of 5:1) for the production of 1,130,737 MT (whole, wet basis) of farmed shrimp in 1999). This is equivalent to a FCR of 2.08, or the consumption of 2.08 kg of fish (pelagic, wet weight basis) for the production of 1.0 kg of shrimp (wet weight basis).

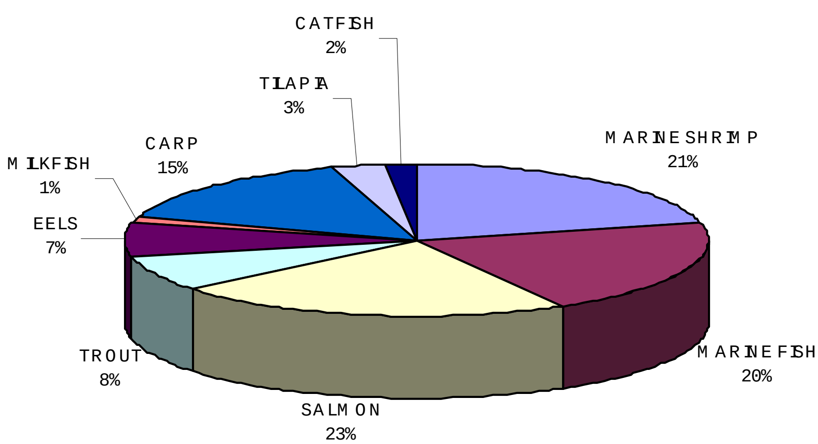


Figure 4. Estimated global use of fishmeal in compound aquafeeds in 1999. Total estimated fishmeal use 2.22 MMT (33.8% of total fishmeal production). Salmon 0.49 MMT, Marine Shrimp 0.47 MMT, Marine Fish 0.45 MMT, Carp 0.33 MMT, Trout 0.17 MMT, Eels 0.16 MMT, Tilapia 0.07 MMT, Catfish 0.04 MMT and Milkfish 0.03 MMT.

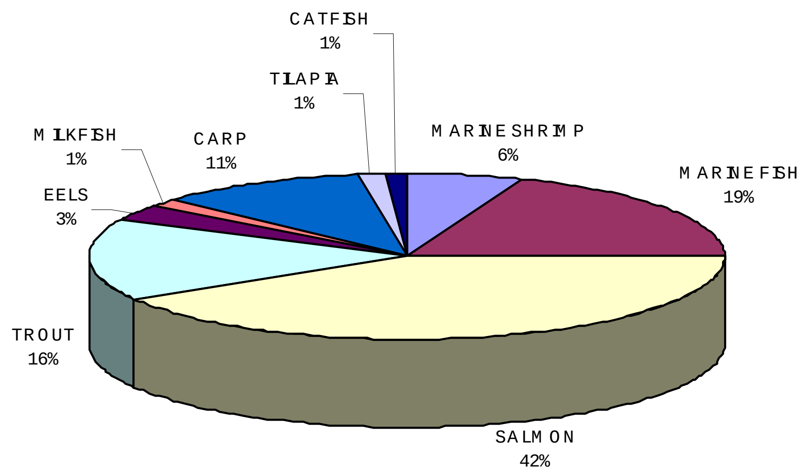


Figure 5. Estimated global use of fish oil in compound aquafeeds in 1999. Total estimated fish oil use 620,333 MT (45.6% total global fish oil production) Salmon 257,927 MT, Marine Fish 117,662 MT, Trout 98,795 MT, Carp 66,769 MT, Marine Shrimp 36,184 MT, Eels 19,127 MT, Milkfish 8,798 MT, Tilapia 8,574 MT and Catfish 6,497 MT

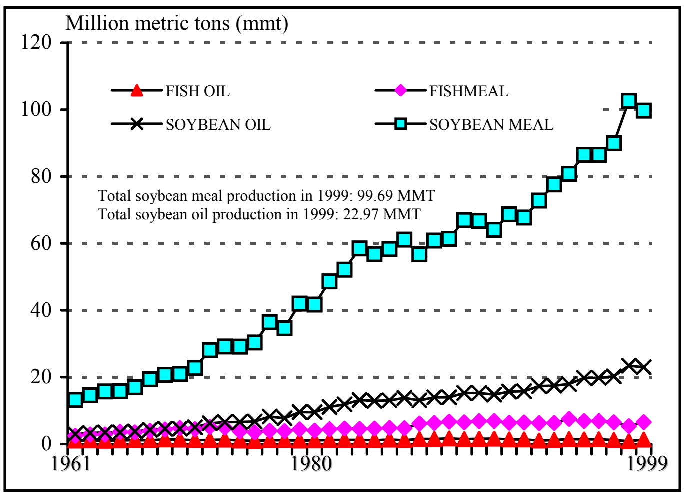
The relationship between dietary fish meal inclusion level and farm FCR on the equivalent amount of pelagics required to produce 1 kg of shrimp biomass can be seen below:

25% fish meal diet – farm FCR 2.0 – pelagics required 2.5 kg   (calculated (0.25 x 5) x 2)
25% fish meal diet – farm FCR 1.8 – pelagics required 2.25 kg
25% fish meal diet – farm FCR 1.6 – pelagics required 2.00 kg
25% fish meal diet – farm FCR 1.4 – pelagics required 1.75 kg
25% fish meal diet – farm FCR 1.2 – pelagics required 1.50 kg
25% fish meal diet – farm FCR 1.0 – pelagics required 1.25 kg
25% fish meal diet – farm FCR 0.8 – pelagics required 1.00 kg (break point)
15% fish meal diet – farm FCR 2.0 – pelagics required 1.50 kg
15% fish meal diet – farm FCR 1.8 – pelagics required 1.35 kg
15% fish meal diet – farm FCR 1.6 – pelagics required 1.20 kg
15% fish meal diet – farm FCR 1.4 – pelagics required 1.05 kg (break point)
10% fish meal diet – farm FCR 2.0 – pelagics required 1.00 kg (break point)

On the basis of the above data, the shrimp farming industry would have to lower its farm FCR from 2 to 0.8, reduce mean dietary fish meal level from 25 to 15% and FCR from 2 to 1.4, or reduce mean dietary fish meal level from 25 to 10% to reach break point', where the weight of pelagics consumed is equivalent to the shrimp produced on a wet weight basis.

Despite the generally optimistic projections concerning the future availability and use of fish meal and fish oil in shrimp feeds and aquafeeds (see Table 11) (Chamberlain and Barlow, 2000; IFOMA, 2000), real concerns exist about the almost total current dependence of intensive farming systems for high value species (i.e., salmonids, eels, marine finfish, and shrimp) upon fish meal and fish oil (Anon, 2000a; Hardy, 2000; Hardy and Tacon, 2001). Apart from the uncertainty of market availability and cost of these finite and valuable wild aquatic resources, there are also growing social and environmental concerns regarding the long-term sustainability and ethics of catching and processing low-value (in marketing terms) yet potentially food-grade fishery resources and feeding them (in particular, pelagic fish species such as anchovy, sardine and mackerel) to high-value farmed aquatic species (Naylor et al., 2000). Instead, this line of argument goes, these fish resources could provide humans with an affordable source of much-needed high-quality animal protein and essential nutrients. Malnutrition is still the number one killer and cause of ill health on Earth (Tacon, 2001a).

As shown in Figure 6, from 1961 to 1999 global production of soybean meal and soybean oil grew substantially: 678% and 685%, respectively, by weight. Soybean meal production increased from 13.19 to 102.62 MMT, and soybean oil from 2.99 to 23.46 MMT. The average growth rate of these two soy products combined was 5.9% per year (compounded). By contrast, fish meal and fish oil production have grown by 161% and 30% since 1961, increasing from 2.51 to 6.55 MMT (fish meal) and from 1.05 to 1.36 MMT (fish oil). The average compounded rate of growth for these fish products was modest: 2.6% and 0.7% per year, respectively.



1999 PRODUCTION

FISHMEAL
6,547,843 mt *Major producers:*
Peru 27.0%, Chile 15.3%, China 10.8%, Japan 6.2%, Thailand 6.1%, Denmark 5.7%, USA 5.4%, Norway 3.7%, Iceland 3.7%, Russian Federation 2.4%, Spain 1.3%.
Production change since 1998: +22.2%

FISH OIL
1,359,988 mt *Major producers:*
Peru 37.8%, Chile 14.8%, USA 9.5%, Denmark 9.5%, Iceland 6.4%, Norway 5.3%, Japan 5.1%, China 2.6%, Spain 1.3%.
Production change since 1998 is 56.1%
Source: FAO (2001).

Figure 6. World Production of fishmeal, fish oil, soybean meal and soybean oil: 1961 to 1999

In view of the urgent need of the aquaculture sector to reduce its dependence upon wild capture fisheries for sourcing its feed inputs (which may not be able to continue providing these resources at current rates), in the long term the use of fish meal and fish oil for shrimp and other compound aquafeeds is expected to decrease (Table 11). Such a decrease will primarily result from progressively increasing external market forces and consumer pressure (rather than purely economic or nutritional forces) placed upon the aquafeed manufacturing and aquaculture sector for the production of more environmentally sustainable or “greener” (in consumers’ eyes) and safer aquaculture produce, including compound aquafeeds (Deguara, 2001; Tacon, 2001b).

The reduced use of fish meal and fish oil in both terrestrial and aquatic compound feeds may be further impacted by the recent discovery that these and other fishery products may be contaminated (depending upon their origin) with environmental contaminants or pollutants, including dioxins (Carvajal Carranza 2000; Cooke and Sellers 2000; Franco 2000; IFOMA 1999, 2001; Starkey 2001). Dioxin is a generic term commonly applied to a class of compounds called polychlorinated dibenzo-p-dioxins (PCDD or dioxins), polychlorinated dibenzofurans (PCDF or furans) and polychlorinated biphenyls (PCBs); collectively known as halogenated aromatic hydrocarbons (McGee, 2000). The upshot of the research is that new limits of dioxins in fish oil, fish meal, compound aquafeeds, and aquaculture produce will very likely soon be imposed on the sector (although this will vary from country to country and region to region). For example, according to IFOMA (2001) the European Commission has issued a list of proposed maximum dioxin levels to take effect January 1, 2002, as follows:

- Fish oil: 6.0 pg/g product (2002), 4.0 pg/g product (2006)
- Fish meal: 1.25 pg/g product (2002), 0.75 pg/g product (2006)
- Compound feed: 0.5 pg/g product (2002), 0.35 pg/g product (2006)
- Fish feed: 2.25 pg/g product (2002), 1.25 pg/g product (2006)
- Fish sold for human consumption: 4.0 pg/g product (2002), 3.0 pg/g product (2006)

The units of measurement are picograms (pg); 1 pg = 10^{-12} grams, or one million millionth of a gram. These limits are thus measured in parts per trillion. Although there is still a great deal of discussion and heated debate concerning the proposed limits, it is clear that in the future aquafeed/aquafeed manufacturers and aquaculture producers will be forced to comply with some limits, either by developing improved fish/fish oil processing methods (for removing dioxins from extracted fish oil, further extracting fish oil from fish meal, or better drying methods) (Anonym 2001a, 2001b) or by using alternative dietary protein and lipid sources.

Moreover, it is likely that in the future there will be increased pressure from retailers and consumers alike for the reduction of fish and plant lipids within aquafeeds and farmed aquatic produce, not because the fat may be a rich or poor source of highly unsaturated fatty acids or cholesterol, but rather due to the simplistic preference for lower fat produce for health reasons. There are, for example, already complaints about the fat content of some salmon produced by aquaculture.

Despite these issues, IFOMA (2000) has estimated that the use of fish meal and fish oil in aquafeeds will continue to increase from 2.32 MMT and 0.72 MMT in 2000, to 3.45 MMT and 1.21 MMT by 2010, to 3.70 MMT and 1.26 MMT by 2015, respectively (Table 11). While in the short term efforts may focus on the use of non-food-grade fishery by-products (i.e., fishery by-catch and discards, and fishmeals produced from fish processing plant wastes and nonfood fishes), clearly in the long term efforts must be placed on utilizing feed resources arising from the much larger terrestrial agricultural plant and animal sectors (Tacon and Forster, 2000).

Use of Terrestrial Animal By-products for Aquafeeds

Terrestrial animal by-products from the livestock industry represent the largest available source of animal proteins and lipids for the animal feed compounder. The terrestrial rendering industry handles over 60 MMT of non-food-grade raw waste materials annually (Ib 2001), compared with just over 26 MMT by the fisheries rendering industry (FAO 2001a). Animal by-product meals derived from the rendering industry include:

- Animal protein meals (meat and bone meal, meat meal, hydrolyzed feather meal, poultry by-product meal, blood meal, and specialized protein blends);
- Fats (industrial tallows, edible beef tallow, lard, yellow grease, feed-grade fats); and
- Miscellaneous products (liver, lung, hatchery waste, hide fleshings, blood/rumen content, etc.).

Although no precise statistical information exists on the global production and availability of the above animal by-product meals, the total volume of these animal by-product meals (ca. 18–25 MMT) is estimated to exceed that of fish meal and fish oils (6–7 MMT) by a factor of 3 (Tacon 2000b). Despite their market availability and lower cost compared with fish meal and fish oil (Table 11), terrestrial animal by-product meals have not generally found widespread use in compound shrimp aquafeeds.

Table 11. Reported ingredient international market price for selected rendered animal by-products and other key feed ingredients.
Sources: *Feedstuffs*, June 26, 2000; Tacon (2000b).

Ingredient	$US/ton
Meat and bone meal (ruminant)	173–225
Meat and bone meal (porcine)	205–243
Flash-dried blood meal	365–395
Poultry by-product meal	210–303
Hydrolyzed feather meal	187–215
Menhaden fish meal	310–410
Anchovy meal	435
Soybean meal (high-protein)	169–214
Cottonseed meal	132–183
Canola meal	106–134
Corn gluten meal	235–265
Prime tallow	8–10 (cents/pound)
Yellow grease	6–10.75 (cents/pound)
Choice white grease	10–11.25 (cents/pound)
Poultry grease	8–9 (cents/pound)

To a large extent, their generally lower nutritional value (compared with fish meal) and sometimes variable composition (depending upon the source and origin of the raw material rendered) have limited their use in aquafeeds (Hertrampf and Piedad-Pascual 2000; Li et al. 2000; Tacon and Akiyama 1997; Williams et al. 1997).

However, the development of improved processing methods by the rendering industry has resulted in the emergence of a new generation of high-quality animal by-products (Anon 2001c; Pearl 2000; Shepherd 1998; Ziggers 2000, 2001), with a consequent improvement in the nutritional quality and feed value of these meals for farmed aquatic species, including shrimp (Davis 2000; Davis and Arnold 2000; Mendoza et al. 1998; Millamena et al. 2000; Smith et al. 2000). For example, Davis and Arnold (2000) showed that a co-extruded soybean/poultry by-product meal mixture (Profound^{TM}) and flash-dried poultry by-product meal could replace up to 80% of the fish meal in a 32%-protein diet (originally containing 30% fish meal) for *P. vannamei,* with no loss in growth or feed performance. Under outdoor tank conditions in another study, total fish meal replacement was done, with no loss in shrimp performance (De Bault et al. 2000). Similarly, recent feeding trials conducted with *P. vannamei* in outdoor experimental zero-water-exchange culture systems at the Oceanic Institute (OI) in Hawaii have shown that high-quality fish meal (72.3% crude protein, 10.9% lipids; highest quality, low-temperature-dried, costing over US$ 1,000/MT) could be totally replaced with either meat and bone meal (55.6% crude protein, 10.6% lipid; costing US$ 200–250/MT) or poultry by-product meal (69.1% crude protein, 15.7% lipid; costing US$ 250–300/m), with little or no significant loss in growth performance, food conversion efficiency, or survival rates (Table 12).

Table 12. Results of feeding trials conducted at the Oceanic Institute with juvenile *P. vannamei* reared in outdoor zero-water-exchange culture systems (stocking density: 77 animals/m^3) and fed a 35% crude protein/9% lipid diet with different dietary protein sources. [1]Feed Conversion Ratio = Feed fed (g) / Weight gain of shrimp (g).
Source: Tacon (2000b).

Measure	Feed type 1: fish meal 22%	Feed type 2: Meat and bone meal 31%	Feed type 3: Poultry by-products 23%
Initial body weight (g, day 0)	1.85	1.88	1.88
Final body weight (g, day 56)	13.40	12.28	12.39
Growth rate (g/week)	1.44	1.30	1.31
Shrimp FCR[1]	1.68	1.76	1.78
Shrimp survival rate (%)	94.3	95.0	95.0

Apart from the obvious economic benefits, the increased use of adequately processed terrestrial animal by-product meals for aquafeeds has the added advantage of converting non-food-grade products with potential negative environmental effects (disposal through dumping or incineration) into high-quality, nutritious, and safe aquaculture foods (Tacon 2000b). Moreover, the recycling of processed animal by-product meals derived from warm-blooded terrestrial animals through a completely different food chain (cold-blooded farmed aquatic animals) may act as a barrier to the intraspecies transfer of mammalian infectious agents (e.g., transmissible spongiform encephalopathies such as bovine spongiform encephalopathy, or BSE) (Anonym 2001c; D'Mello 2001; Machin 2001; Willesmith 1998).

Use of Terrestrial Plant By-products and Single-cell Proteins for Aquafeeds

Although animal protein and lipid sources are generally regarded as the preferred and natural nutrient source for shrimp, due to the natural benthic and scavenging feeding habits of shrimp (Focken et al. 1998; Gautier et al. 2001; Hunter et al. 1987; Nunes and Parsons 2000), plant and single-cell proteins remain a largely untapped primary feed resource for farmed shrimp. For example, the total global production of plant oilseed meals and cakes in 2000 was estimated to be 166.7 MMT (Figure 7), of plant pulses 54.7 MMT (Figure 8), and plant oils and fats 90.2 MMT (Figure 9) (FAOSTAT Agriculture Database, 02 May 2001). Despite their ready availability, the use of plant by-product meals is generally restricted to low to moderate dietary inclusion levels (typically between 15 to 35%), and plants are viewed as a secondary source of dietary nutrients rather than a primary source (Devresse 1995, 1996; Hertrampf and Piedad-Pascual 2000; O'Keefe 1998; Tacon and Akiyama 1997). Plants generally have lower nutritional value than animal protein sources, either because of inherent nutrient deficiencies and imbalances (Davis, 2000; Li et al. 2000; Smith et al. 2000) or the presence of specific antinutritional factors (Dong et al. 2000; Tacon 1997).

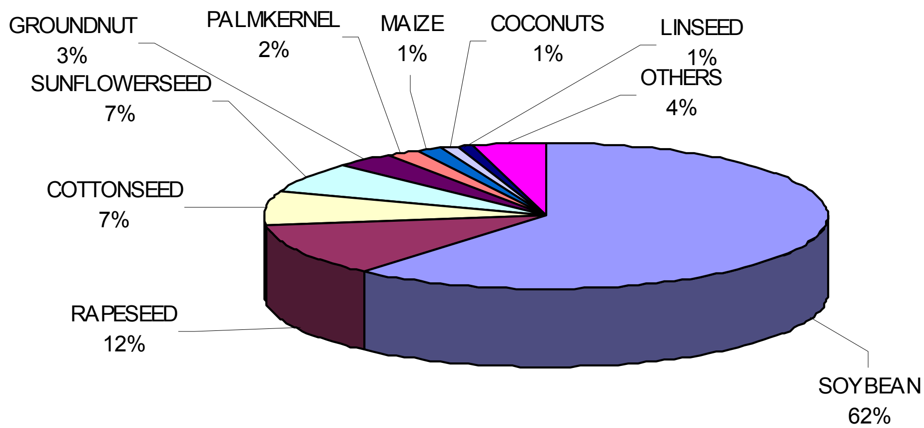


Figure 7. Global production of plant oilseed cake and meal in 2000: Total: 166.73 MMT. Soybean 101.7 MMT, Rapeseed 19.9 MMT, Cottonseed 12.5 MMT, Sunflowerseed 11.2 MMT, Groundnut 5.8 MMT, Palmkernel 3.2 MMT, Maize 2.2 MMT, Coconuts 1.9 MMT, Linseed 1.5 MMT and others 6.9 MMT. Source: FAOSTAT Agriculture Database, May 2001.

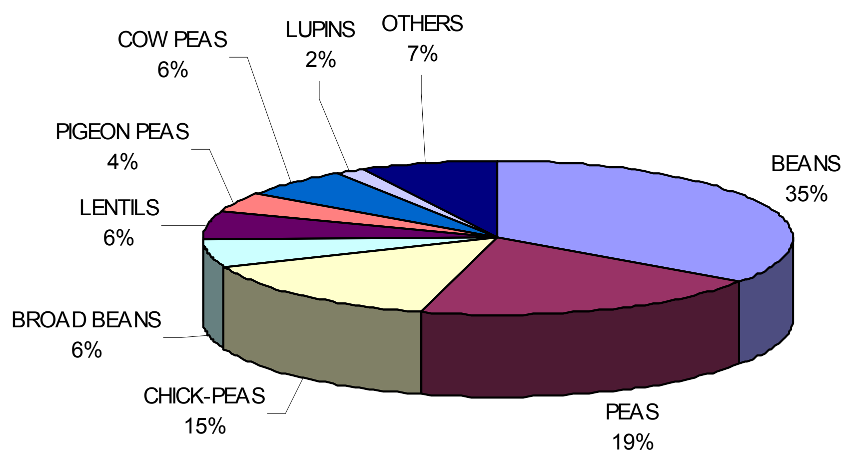


Figure 8. Global production of plant pulses in 2000. Total: 54.7 MMT. Beans 18.9 MMT, Peas 10.7 MMT, 8.0 MMT, Broard Beans 3.3 MMT, Lentils 3.1 MMT, Cow Peas 3.3 MMT, Pigion Peas 2.3 MMT, Lupins 1.0 MMT and Other 4.1 MMT. Source: FAOSTAT Agriculture Database, May 2001.

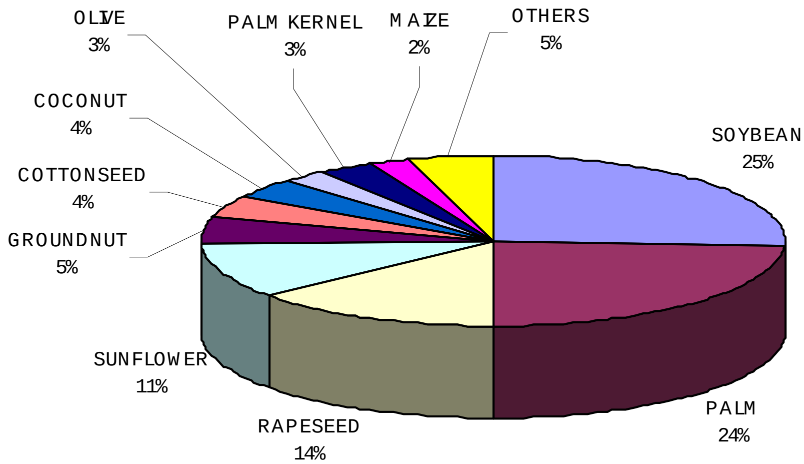


Figure 9. Global production of plant oils and fats in 2000. Total: 90.16 MMT. Soybean 23.2 MMT, Palm 22.0 MMT, Rapeseed 12.4 MMT, Sunflower 9.5 MMT, Groundnut 4.6 MMT, Cottonseed 3.8 MMT, Coconut 3.3 MMT, Olive 2.5 MMT, Palmkernel 2.7 MMT, Maize 2.0 MMT and Others 4.2 MMT. Source: FAOSTAT Agriculture Database, May 2000.

Shrimp (similar to all other farmed animals) do not have a specific dietary requirement for fish meal, squid meal, or shrimp meal, but rather a requirement for about 40 or so essential nutrients within a balanced diet. The nutrient composition of marine animal protein sources approximates very closely the known dietary requirements of shrimp, so it is no surprise that these feed ingredients usually have a higher nutritional value for shrimp than individual plant feedstuffs (D'Abramo et al. 1997). Therefore, the challenge of feed formulation is to blend complementary plant and animal feed ingredients to obtain a more balanced nutrient profile. With this in mind, several researchers have successfully managed to replace fish meal in shrimp feeds with complementary protein mixtures, including a co-extruded soybean meal/poultry by-product meal mixture (Profound™; Davis and Arnold 2000) and soybean meal/feather meal hydrolysate mixture (Roberto et al. 2000). Moreover, with advances in feed ingredient processing and feed formulation (including the use of feed enzymes and feeding attractants), promising results have been obtained with a variety of processed plant feedstuffs under experimental conditions, including:

- Soybean meal/soybean protein concentrate (Davis 2000; De Bault et al. 2000; Ley 2001; Lim and Dominy 1990).
- Rapeseed/canola meal (Cruz-Suarez et al. 2001a; Lim et al. 1997).
- Pea meal (Cruz-Suarez et al. 2001a; Davis et al. 2001).
- Cottonseed meal (Lim 1996).
- Lupin meal (Smith et al. 2000; Sudaryono et al. 1999).
- Cowpea and mung bean (Eusebio and Coloso 1998).

Similarly, recent feeding trials conducted with juvenile *P. vannamei* (1.4 g initial body weight, stocking density 77/m^3) in outdoor experimental zero-water-exchange culture systems at OI have shown that high-quality fish meal (72.3% crude protein, 10.9% lipid) could be totally replaced with soybean protein concentrate (64.7% crude protein, 0.6% lipid) within a 30% crude protein diet with little or no significant loss in growth performance, food conversion efficiency, or survival over a 10-week growth period (Tacon et al. 2001b). By contrast, subsequent studies conducted at OI with juvenile *P. vannamei* (stocking density 66/m^3) within the same zero water-exchange culture systems with animals fed a 35% crude protein diet based upon the use of a mixture of vital wheat gluten (75.3% crude protein/2.3% lipid) and soybean protein concentrate, showed reduced shrimp growth compared with animals fed an equivalent diet based upon the use of a mixture of high quality fish meal and squid meal (76.0% crude protein/4.7% lipid; Argue et al. 2001). Reduced growth performance was also observed with shrimp fed a 30% crude protein diet in which corn gluten meal was used as a total replacement for fish meal (Tacon et al. 2001b).

In addition to plant proteins, it is also worth mentioning here the good long-term prospects of using single-cell proteins (SCP), including bacteria, fungi/yeast, and algae, as dietary fish meal replacements for shrimp. Single-cell proteins produced from renewable resources such as hydrocarbons (e.g., methane) and/or agricultural waste streams probably represent the best long-term alternative to fish meal and fish oil for the animal and aquafeed industries (Anon 2000b). For example, according to Wang and Liang (2001), yeast represents the second most preferred protein source after fish meal for the Chinese shrimp, *P. chinensis*. However, in the absence of any long-term growth studies using SCP as a dietary replacement for fish meal and fish oil for shrimp, it is not possible to give specific recommendations at this point.

Challenge 4

- The potential value of feed additives such as free amino acids, feed enzymes, chemo-attractants and feeding stimulants, probiotics, and immunostimulants for farmed shrimp needs to be recognized, and practical application technologies for their successful incorporation in manufactured aquafeeds need to be developed.

As national and international pressure increases for developing and using safer, more environmentally sound, and sustainable shrimp aquafeeds and feeding technologies, using feed additives will gain increasing importance (Barrows 2000; Cuzon 1996; Guerin 1998). Feed additives that may be useful include:

- **Free amino acids:** used singly or in mixtures to reduce dietary protein levels and nitrogen excretion, to overcome dietary amino acid deficiencies resulting from fish meal replacements, or as feeding stimulants (Best and Gill 1998; Chen and Chou 1996; Chen et al. 1992; Davis and Miles 2001; Divakaran 1994; Divakaran et al. 1998; Fox et al. 1995; Green et al. 2001; Guillaume 1997; Kaushik 1998; Koshio et al. 1996; Rosas et al., 1998; Swick 1994).
- **Feed enzymes:** used singly or in mixtures to increase carbohydrate and mineral digestibility and reduce nutrient (e.g. phosphorus) loss to the aquatic environment (Baker et al. 2001; Baldia 1994; Buchanan et al. 1997; Cuzon 1996; Davis and Arnold 1998; Davis et al. 1998; Divakaran and Velasco 1998; Guerin 1998; Lobo 1999, 2000; Sugiura and Hardy 2000).
- **Chemoattractants and/or feeding stimulants:** used to increase feed palatability and stimulate feed intake (especially when applied to plant-based rations containing low levels of marine protein sources), increase growth (by minimizing the time the feed remains uneaten in water and thereby minimizing nutrient loss through leaching), and reduce feed wastage (Cruz-Suarez 2001; Cruz-Suarez et al. 2000a; Cuzon 1996; Guerin 1998; Janssen and Peschke-Koedt 1996; Lee and Meyers 1997; Lopez et al. 1998; Mendoza et al. 2000, 2001; Millamena 1996; Montemajor et al. 1998).
- **Probiotics:** live micro-organisms (e.g., bacteria and fungi) and/or their processed products are used as dietary supplements or added directly to the water to stabilize or enhance a healthful and appropriate microbial community in the gastrointestinal tract of the cultured shrimp and/or within the culture system, so as to improve growth, survival, and/or disease resistance (Anon 1997; Austin et al. 1995; Cuzon 1996; Devresse et al. 1997; Douillet 2000; Green and Green 2000; Guzman 1993; Horowitz and Horowitz 2000a, 2001; Intriago et al. 1998; Karunasagar et al. 2000; Montoya and Velasco 2000; Moriarty 1997b; Newman 2001; Samocha et al. 1998; Sealey 2000; Sonnenholzner

and Boyd 2000). However, it is important to mention here that although good scientific evidence exists concerning the beneficial effects of probiotics on shrimp performance and health under clear-water hatchery conditions, this has not always been the case under practical pond grow-out conditions, where resident aquatic/sediment microbial flora already exists (Fegan 2000).

- **Immunostimulants:** used to stimulate the nonspecific immune system mechanisms of shrimp and thus increase disease resistance (Anon 2000c; 2000d; Bachere 2000; Burbano 2000; Castille et al. 2000; Cedeno et al. 2000; Cruz-Suarez 2001; Cuzon 1996; Devresse et al. 1997; Devresse 2000a, 2000b; Dugger 1998; Heng and Guangyou 1996; Lavens and Sorgeloos 2000; Le Moullac et al. 1998; Le Moullac and Haffner 2000; Mukhi et al. 1999; Newman 2000a, 2000b, 2000c; Rodriguez et al. 2000; Russell 2000; Sealey 2000; Scholz et al. 1999; Smith and Clark 2000; Vargas-Albores and Yepiz-Plascencia 2000; Wang et al. 1999).
- **Miscellaneous:** Other additives that can be used in shrimp feeds include antioxidants, mold-inhibiting compounds, pigments, and to a lesser extent chemotherapeutants and hormones (Barrows 2000; Castille et al. 2000; Hertrampf and Piedad-Pascual 2000; Meyers 1998; Toullec et al. 1991).

In conclusion, the ultimate success of many of these feed additives will depend to a large extent on whether appropriate application technologies and techniques for incorporating the additives in manufactured aquafeeds can be developed. Coated or otherwise protected forms (so as to withstand high feed-processing temperatures, delay uptake, and reduce loss through leaching), and improved post-pelleting application and drying techniques will need to be developed as well (Anon 1998; Barber 2000; Best 1999; Flower 2001; Gill 2000b; Langdon and Buchal 1998; Sunderland 2001; Tsang 2001).

Challenge 5

- There is an urgent need to maximize dietary nutrient utilization efficiency and minimize nutrient loss and feed wastage resulting from pellet disintegration, nutrient leaching, and/or overformulation.

Developing improved feed formulation and manufacturing techniques provides a promising route toward this goal. The following elements are included:

- Better selection and use of binders or feed ingredients with positive binding and water stability attributes (Barrows 2000; Cuzon 1996; Cuzon and Gehin 1998; Devresse 1998; Dominy and Lim 1991; Dominy et al. 2001; Lim and Cuzon 1994; Tacon and Obaldo 2001).
- Selecting easily digestible feed ingredient sources over ingredient sources containing a high proportion of indigestible matter, such as fiber, complex carbohydrates, or ash (Cuzon and Gehin 1998; Sugiura and Hardy 2000; Suresh and Zendejas 2000).
- Selecting and using specific feed additives or feed ingredients with attractant or feeding stimulant properties (see feed additive section above).
- Setting key nutrient levels (i.e., for crude protein, lipids, carbohydrates, and total energy) that are tailored to the intended farming system and shrimp stocking density, rather than on theoretically optimum nutrient requirement levels. This step would avoid overformulation and unnecessary nutrient loss (Lawrence 1996a, 1996b; Lawrence and Lee 1997; McIntosh 2000a; Tacon 1996, 1999a, 1999b; Villamar 1999).

In addition to these measures, there is also a need to maximize dietary nutrient utilization efficiency and minimize nutrient loss and feed wastage. Effective steps focus on developing and using improved feed processing/manufacturing techniques, including:

- Implementing finer grinding and micropulverization techniques, prolonged low-pressure steam conditioning, post-conditioning, and using increased die compaction ratios (25 or more) to improve stability in water and minimize pellet disintegration (Barrows and Hardy 2000; Bartone 1999;

Devresse 1998; Erickson 2000; Gill 2001a, 2001b; Halvorsen 2000; Lim and Cuzon 1994; Obaldo et al. 1998; Tan and Dominy 1997).

- Using extrusion cooking techniques in order to increase nutrient digestibility (starch hydrolyzation and gelatinization, protein denaturation), destroy antinutritional components (trypsin, lectins), inactivate of undesirable enzymes (urease, peroxidase, lipoxidase, myrosinase), destroy toxic components (glucosinolates, gossypol, aflatoxin), destroy microorganisms (bacteria such as salmonella, yeasts), improve air quality (by reducing feed dust), increase shrimp growth efficiency (increased fat intake, reduce feed wastage), and improve pond water stability (Barrows and Hardy 2000; Coelho 1994; Dong et al. 2000; Kearns 1998; Kiang 1993; Lucht 2001; Obaldo et al. 1999a, 1999b, 2000; Riaz 1997, 2001; Rokey and Huber 1994; Rokey 2001).
- Developing improved pre- and post-pelleting coating techniques for the application and/or protection of essential heat-sensitive nutrients (vitamins, pigments, enzymes, probiotics, attractants, lipids, etc.) to maximize dietary nutrient utilization efficiency and/or minimize nutrient loss through leaching (see feed additives section).
- Making improvements to optimize feed/pellet size, shape (possibly including feeding blocks), density, hardness, moisture content, texture, and color, to elicit maximum nutrient utilization efficiency and minimize feed wastage (Akiyama 1993; Nunes and Parsons 1998; Obaldo and Tacon 2001).

Challenge 6

- The industry needs to recognize the increased dietary nutrient requirements of shrimp for the maintenance of optimum health and disease resistance under practical farming conditions.

In contrast to indoor hatchery/tank-based culture systems, where strict controls usually maintain optimum water quality and a stable aquatic environment, shrimp raised outdoors in earthen ponds or tanks are usually continually exposed to varying ambient conditions and stress, including handling, fluctuating/deteriorating water quality and benthic environment, and disease agents. All animals (including shrimp) have additional dietary nutrient requirements for optimum health and well being, over and above that normally required for optimum growth and feed efficiency. Unfortunately, the majority of nutrient requirement studies have been conducted under indoor laboratory conditions—yet even then, the animal subjects generally exhibit sub-optimal growth (Tacon 1996).

To date, nutrients and dietary components reported to improve the health and/or disease resistance (including immune response) of farmed finfish and crustaceans include essential amino acids (lysine, methionine, tryptophan, arginine, histidine, leucine, isoleucine), nucleotides, polysaccharides (peptidoglycans, beta 1,3 and 1,6 glucans, lipopolysaccharides), essential fatty acids (18:2n-6, 18:3n-3; 20:4n-6, 20:5n-3, or 22:6n-3, depending upon species), sterols, phospholipids, essential minerals (P, K, Mg), trace elements (Fe, Zn, Mn, Cu, Se, I), vitamins (B_1, B_2, B_6, B_{12}, pantothenic acid, niacin, biotin, folic acid, inositol, choline, D_3, A, K_3, E, and C) and carotenoids (Tacon 2000c).

For example, strong evidence suggests that the dietary requirement of shrimp for certain vitamins and essential nutrients may be higher than that required for normal growth and development under stressed or adverse environmental conditions and for increased immunocompetence and disease resistance, including the dietary requirement for:

- Vitamin C (Boonyaratpalin 1996; Chou 1996; Kanazawa 1996; Kontara et al. 1997; Kurmaly and Guo 1996; Lavens and Sorgeloos 2000; Merchie et al. 1998).
- Vitamin A (Pangantohon et al. 1996).
- Astaxanthin (Kurmaly and Guo 1996; Pangantohon et al. 1996; Merchie et al. 1998).

- Long-chain polyunsaturated fatty acids and phospholipids (Kanazawa 1996; Chim et al. 2000; Coutteau et al. 2000; Lavens and Sorgeloos 2000).
- Other vitamins and nutrients (Bird 1997; Dveresse 1998).

Challenge 7

- Industry members need to recognize that feed ingredients and compound aquafeeds can act as vectors that transmit pathogens to farmed shrimp. This risk needs to be reduced by developing and using appropriate feed processing/manufacturing techniques that destroy potential pathogens and microbial contaminants, and/or by selecting and using nonmarine, specific pathogen-free (SPF) feed ingredients.

The high proportion of fishery by-product meals usually incorporated in shrimp aquafeeds and the frequent use of natural marine food items as supplementary feed items (either alone or in farm-made aquafeeds) creates a potential risk of disease transmission to the cultured shrimp (Camarena-Conchas et al. 1998; Chamberlain 1997; Devresse et al. 1997; Fast and Menasveta 2000; Fegan 2001; Gill 2000a; Intriago et al. 1996; Jory 1995b; Kutty 1995; Limsuwan 1996; Merchie et al. 1997; Phillips 1995; Prior et al. 2001; Rodrigues et al. 2001; Supamattaya 1996; Tacon and Forster 2000).

The above risk, however small, means that there is a real need to safeguard the shrimp farming community by developing and using appropriate feed processing methods, including heat processing and irradiation techniques (Coelho 1994; Gill 2000a; Said 1996), or by excluding from the diet ingredients of marine/invertebrate origin that could act as potential pathogen carriers. In the first instance, the re-feeding of feed ingredients derived from nonprocessed and/or produced from aquaculture products (including fish and shellfish processing wastes, fish meal, shrimp meal, dead animals, etc.) should be avoided at all costs (FAO 2001b; UKASTA 2001). However, this is currently not the case within most shrimp producing countries where the use of shrimp meal and shrimp head meal is still permitted, even preferred, within shrimp aquafeeds.

Challenge 8

- The farmed shrimp industry needs to reduce its dependence on wild-caught seed and broodstock by developing improved processing and manufacturing techniques for the production of larval, nursery, and broodstock feeds.

In contrast to the majority of freshwater finfish/crustacean farming systems, the marine shrimp farming sector is still very much dependent on marine capture fisheries for sourcing its broodstock and, to a lesser extent, its larvae and seed (Rosenberry 2000). Apart from avoiding the risk of disease introduction from wild-caught seed and/or broodstock animals (see previous section), the industry also needs to automate production methods by implementing simple feeding systems that use artificial compound aquafeeds. Another benefit of such systems is reducing production costs.

Little published information exists concerning the dietary nutrient requirements of shrimp broodstock for optimum maturation/reproduction and egg/sperm production (Alava et al. 1993a, 1993b; Akiyama et al. 1991; Browdy 1999; Cahu 1998; Chou 1996; Harrison 1997; Marsden et al. 1997; Menasveta et al. 1994; Millamena 1996; Pangantihon-Kuhlman and Hunter 1999; Pangantihon et al. 1996; Quinitio et al. 1996; Tirado et al. 1998; Wouters et al. 2000; Xu et al. 1994). However, as with humans, it is generally believed that the dietary nutrient requirements of shrimp broodstock vary depending upon their size and developmental status (subadult, mature adult, spawning or post-spawning) and sex (female or male). The dietary requirements for those nutrients directly involved in the maturation/reproduction process are known to be over and above that usually required for normal growth and development (Tacon and Izuierdo 2000).

The need is obvious to culture and maintain specific pathogen free (such as High Health®) shrimp stocks and breeding centers for the production and distribution of disease-free broodstock and larvae to farmers (Bullis and Pruder 2000; Juarez 2000; Pruder 1994; Rosenberry 2000; Wyban 2000). Appropriate feed processing/manufacturing techniques must also be developed for the commercial production of cost-effective artificial feeds for shrimp broodstock and hatched larvae. Feed processing/manufacturing techniques currently under investigation include the following.

- Larval feeds—the development and manufacture of water-stable larval shrimp feeds, including liquid larval feeds (water-stable encapsulated nutrient beads suspended in a liquid medium) (McGoogan 2001; Nates 2001; Villamar 1999), micro-encapsulated dry particulate feeds (Jones et al. 1997; Langdon 2000a; Nates 2001), micro-bound dry particulate feeds (Barrows and Lellis 2000; Tacon 1986; Teshima et al. 1993), and complex dry micro-particulate feeds (Langdon 2000b). For general reviews on larval shrimp nutrition, see Garcia (1998) and Jones et al. (1997).
- Broodstock feeds—the development and manufacture of water-stable dry or semi-moist broodstock maintenance feeds using cold extrusion, steam/compression pelleting, or cooking extrusion techniques (Barrows and Hardy 2000; Marsden et al. 1997; Pinon et al. 1998; Wouters et al. 2000).

Finally, it is important to mention here that certain shrimp species reproduce more readily in captivity than others, and consequently are less stringent in their requirements for fresh food organisms (such as fresh bloodworms and/or squid). For example, species that are reportedly readily able to reproduce in captivity using conventional artificial feeds include *P. chinensis, P. japonicus, P. indicus, P. merguiensis* and *Metapenaeus ensis* (Hoang 2001; Ma Shen 1997; Rosenberry 2000).

Challenge 9

- Shrimp farmers need to maximize feed conversion efficiency and minimize feed losses and related deleterious environmental impacts by developing improved on-farm feed handling and management methods.

The ultimate biological, economic, and environmental performance of an aquafeed is dependent not only on its nutrient content and physical characteristics but equally also on its handling and management in the farm production unit (Tacon 1995). Moreover, unlike with conventional finfish aqualculture, the unique feeding habits of shrimp dictate that the feed remains in water for considerable periods of time before being consumed (usually for several hours), and that the feed be administered under cloudy/murky pond-water conditions. It is not usually possible to directly observe the feeding response of shrimp. It follows, therefore, that the ultimate choice of feeding strategy employed by the farmer will have a profound effect upon the biological and economic performance of the feed and its potential environmental impact (Akiyama 1993, Akiyama and Chwang 1989; Chamberlain 1997; Chanratchakool et al. 1995; Cook and Clifford 1997a; Cruz 1991; Jory 1995b; Lawrence 1995, 1996b; Martinez-Cordova et al. 1998a; New 1998; Nunes 2000, Nunes 2001a, 2001b; Sanhotra 1994; Tacon 1995; Treece 2000).

To illustrate the importance of individual on-farm feeding and shrimp production methods, it is perhaps useful here to summarize observed variations in reported Feed Conversion Ratios (FCR). One example: 174 farms in Thailand that used the same commercial pelleted shrimp diet reported FCRs ranging from 1.0 to 2.6 (mean FCR, 1.6–1.8; Tacon 1995). This variability is similar to that reported by ADB/NACA (1998), which surveyed over 4,802 shrimp farms in Asia and reported mean country FCRs ranging from 1.38 to 2.08 for intensive shrimp farms (mean 1.85), 0.38 to 2.70 for semi-intensive shrimp farms (mean 1.78), and 0.05 to 1.43 for extensive shrimp farms (mean 0.41). More recent country estimates for average shrimp FCR in the leading Asian shrimp-producing countries include 1.8 (Thailand), 1.9 (Indonesia), 2.0 (India), 2.3 (China), and 2.5 (Vietnam) (Dr. Chingchai Lohawatanakul/Dr. Chen Ming

Dang, Charoen Pokphand Foods Public Company Ltd – personal communication, June 2001). Similar variations have recently been reported in specific regions within the same country. Nunes and Suresh (2001b) reported that the observed FCR at 20 shrimp farms in northeastern Brazil ranged from 1 to 1.6 (mean 1.2). These variations are primarily due to the use of different on-farm management practices by individual farmers, including variations in shrimp stocking density, farm/pond size, water management, pond fertilization, and feed management, including the skill and experience of the feeding technician. For example, in Thailand farm size and ownership has been found to have a significant effect on FCR, with smaller family-run farms generally reporting lower FCRs than larger commercially-operated farms (Anon 1992).

In view of such variation in FCR, it is clear that the overall nutrient budgets of shrimp farms will also vary from farmer to farmer, region to region, and country to country, depending upon the farming system employed and diet/feeding method used. Despite this, some authors have attempted to calculate nutrient budgets under practical farming conditions. For example, Briggs and Funge-Smith (1994), calculating the nutrient budget of some intensive shrimp ponds in Thailand, estimated that only 23% of the total pond nitrogen input (TPNI; 92% derived from feed) and 12% of the total pond phosphorus input (TPPI; 51% derived from feed) was incorporated into new shrimp (*P. monodon*) biomass over the production cycle, and that 22% of the TPNI and 7% of the TPPI was released from the pond through routine water exchange. Similarly, Boyd and Teichert-Coddington (1995) calculated the nutrient budgets of carbon (C), nitrogen (N), and phosphorus (P) for the production of *P. vannamei* reared under semi-intensive pond culture conditions, and reported shrimp nutrient recovery rates of 11.5% for C, 45.3% for N, and 21.3% for P. However, commonly used shrimp nutrient recovery rates range from 20 to 40% for N and 10 to 25% for P (Boyd 1999a; Burford et al. 2001; Davis and Arnold 1998; Dierberg and Kiattisimkul 1996; McIntosh 2000b; Teichert-Coddington et al. 1998; Teichert-Coddington et al. 2000; Wang and Liang 2001).

Reported waste loading rates per 1,000 kg of harvested shrimp have ranged widely, from 10 to 117 kg for N and 9 to 46 kg for P, depending upon FCR (Anon 1993a; Beveridge et al. 1998; Boyd and Teichert-Coddington 1995; Briggs and Funge-Smith 1994). For example, according to the Asian Shrimp Culture Council (Anon 1993a), the calculated waste loading rates per 1,000 kg of harvested shrimp would be as follows:

- FCR 1.0 Organic Matter 500 kg, N 26 kg, P 13 kg
- FCR 1.5 Organic Matter 875 kg, N 56 kg, P 21 kg
- FCR 2.0 Organic Matter 1,250 kg, N 87 kg, P 28 kg
- FCR 2.5 Organic Matter 1,625 kg, N 117 kg, P 38 kg

It is evident, then, that whether a diet or feeding regime can be considered environmentally friendly will depend to a large extent upon the farming system and aquatic environment in which the shrimp are reared, and in particular whether a closed or open farming operation is used. For the purposes of this paper, the term environmentally friendly is defined as encompassing those feeds and feed management practices that have little or no adverse effects (resulting from their manufacture and/or on-farm use) upon the surrounding aquatic, terrestrial or aerial environment of the intended aquaculture and/or feed mill operation (Tacon and Cruz 1999).

As a result of pressure for increased biosecurity, and disease and effluent control (Bullis and Pruder 2000), the shrimp aquaculture industry in many countries has increasingly been developing biosecure closed shrimp production systems, including zero-water-exchange or recirculating culture systems employing in situ biofiltration techniques (Autrand and Vidal 1995; Avnimelech 2000a, 2000b; Cohen et al. 2001; Jory et al. 2001; McIntosh 1999a; McNeil 2000; Velasco and Lawrence 2000b) or external biofiltration techniques (Anon 1996a, 1996b; Moss et al. 1998; Lee 2000; Ogle and Lotz 2000, 2001; Reid and Arnold 1992; Van Wyk 2000). For example, the percentages of shrimp farms now operating closed farming systems in each country in Asia have been estimated as follows: Thailand (95% of all farms), Indonesia (25%), Vietnam (10%), and China and India (5% each) (Dr. Chingchai Lohawatanakul/Dr. Chen Ming Dang, Charoen Pokphand Foods Public Company Ltd – personal communication, June 2001). Similarly, Treece and Hamper (2000) reported that through water re-use, coupled with reduced stocking densities (down from 50 to 36 animals/m^2) and increased aeration (up from 20 to 25 hp/ha), Texas shrimp farmers were able to reduce their solids discharges from 3.6 kg total suspended solids (TSS) per kg of shrimp produced in 1994 to 0.05 kg TSS/kg shrimp in 1998, and ammonia discharges from 50g/kg shrimp in 1994 to 0.4g/kg shrimp produced in 1998. Ammonia discharges were also reduced by providing multiple feedings (up to four times per day) and applying lower-protein feeds. Of course, the percentage of closed systems depends entirely on how one defines "closed" given the extensive use of inputs and the production of effluents.

Open farming systems pose the greatest risk of polluting the surrounding and neighboring aquatic environment with uneaten feed (including dissolved nutrients) and fecal/excretory waste streams (Tacon et al. 1995). The risks are perhaps highest for those farmers still using wet/moist feeds, due to their usually poor water stability. For example, deteriorating water quality resulting from the use of fresh/wet feeds (trash fish, shelled clams, etc.) have been reported recently in China (ADB/NACA 1998; Ma Shen 1997; Rosenberry 2000; Xiang 2000; Xu 2000).
In addition to the above, the following aspects of on-farm feed management need to be optimized to maximize feed efficiency and minimize feed wastage.

- **Feed transportation:** Once the shrimp feed leaves the feed manufacturer, it must be transported as quickly as possible to the farmer, and during transportation (either by road, rail, ship or air) the feed must be stored under cool, nonhumid, well-ventilated conditions, not be directly exposed to sunlight or contact with water. For additional guidelines on good feed transportation management practices, see FAO (2001b), Jory (1995b) and O'Keefe (2000).
- **Feed storage:** Conditions for storage and transportation are similar; manufactured feeds are highly perishable products with a finite shelf life and should be stored accordingly. In general, two types of storage facilities are required on a farm: a building/shed for storing large quantities of bagged feeds, and a smaller storage facility (i.e., shed, silo, bins, or similar) alongside the shrimp production pond if required. The latter is particularly important for farmers operating large farms with large production ponds, where feeds may remain outside for up to a day. For additional guidelines and information on good on-farm feed storage management practices, see Akiyama, Dominy and Lawrence (1991), Cruz (1996), FAO (2001b), Jory (1995b), O'Keefe (2000) and SEAFDEC Feed Development Section (1994).
- **Feed application method:** Farmers need to determine the optimum feed application method and feeding regime, including choosing between 1) manual or automated feeding, 2) feeding by broadcasting or submersible feeding trays, 3) monitoring feed intake and shrimp growth/survival by periodic netting and/or by visual inspection of feeding trays, 4) feeding to match appetite by visual observation or by using a fixed feeding regime, 5) adjusting the frequency and timing of feed application.

Although in the past, the choice of feed application method and feeding regime were largely dictated by the size of the shrimp farm and production unit, it is now generally recognized that compound feeds should be fed on a "little and often" basis (to minimize nutrient loss through leaching, dissolved oxygen levels permitting), using a feeding tray application /monitoring system in pond production systems. Feeding trays and frequent monitoring help farmers to control shrimp diseases and water quality, but these methods work better with smaller ponds/production units. The size of such units in the Americas has been steadily decreasing to incorporate these more effective methods. In Asia (where farmers generally have smaller farms and production ponds) it has long been known that small family-managed shrimp farm operations generally have lower FCRs (average 1.6) than larger corporate operations (average 2.0) (Anon 1992, 1994).

The advantages of using feeding trays for monitoring and/or administering feed to the shrimp include that they 1) reduce FCR by eliminating over- and under-feeding, 2) reduce feed usage and wastage due to overfeeding, 3) prevent pond bottom deterioration and water quality deterioration due to excess feed accumulation, 4) facilitate adjustment of feeding rates to shrimp appetite, shrimp developmental stage, and environmental conditions, including molting activity, 5) serve as a useful tool for estimating shrimp survival and monitoring shrimp health, 6) help provide controlled administration of medicated feeds, and 7) offset increased labor costs by reducing FCR and improving pond conditions—providing increased economic benefit for the farmer (Anonym 2000; Artites et al. 1996, Bador et al. 1998; Cook and Clifford 1997b; Cruz 1991; Jory 2001; Nunes and Suresh 2001b; Rosenberry 1999; Viacava 1995). For additional guidelines and information on good on-farm feed application methods, see Chanratchakool et al. (1995), Cook and Clifford (1997b, 1998), Cortes-Jacinto, Villarreal and Portillo (1998), Cruz (1991, 1996), Higuera (1999), Jackson (2000), Jory (1995b, 2001), Jory et al. (2001), Lawrence et al. (1998, 2001), Lee and Lawrence (2001), Molina and Pina (2000), Nunes (2000, 2001a, 2001b), Nunes and Suresh (2001b), Robertson, Lawrence and Castille (1993) and Rosenberry (1999, 2000).

Challenge 10

- Shrimp growers need to recognize the key roles played by micro-organisms, not only as a source of dietary nutrients for cultured shrimp but also in maintaining the productivity, stability, and health of shrimp production systems.

As in terrestrial ecosystems, microorganisms play an essential role in maintaining the health and stability of aquatic ecosystems, in both conventional open-pond production systems and closed zero-water-exchange production systems. Apart from directly supplying dietary nutrients for the cultured shrimp (see previous sections on nutrient requirements and feed additives), micro-organisms are also essential for harnessing and/or removing potentially toxic substances/nutrients from the water column and benthos, including shrimp fecal wastes and metabolites (Bratvold and Browdy 1998; Bratvold et al. 1999; Horowitz and Horowitz 2000b, 2000c; McIntosh 2001; McNeil 2000; Montoya and Velasco 2000; Moriarty 1997a; Moss 2000; Moss and Pruder 1995; Peterson 2000; Tacon 1999b; Tacon et al. 2000; Thompson et al. 2000).

Outdoor zero-water-exchange culture systems are generally operated as completely closed farming systems, with no water exchange for the duration of the culture cycle other than that added to the system to make up for evaporative losses. Shrimp in such systems grow by consuming both externally supplied compound aquafeeds and endogenously produced living microbial food organisms, or "floc." Floc is a complex mixture of microorganisms, including bacteria, algae, fungi, protozoans, metazoans, rotifers, nematodes and gastrotrichs. (Bratvold and Browdy 1999, 2001; Tacon et al. 2002). The organisms found in the flocs from zero-water-exchange culture systems, and the floc from activated sludge (Curds 1992). In zero-water-exchange culture systems, unlike in traditional open or flowing-water pond-based culture systems and those normally encountered in marine and lake snow, the shrimp is essentially changed from a single-stomached animal, where micro-organisms generally play a limited (although important) role in digestion and nutrient supply, to the equivalent of a multi-stomached animal. The floc provides an in situ microbial aerobic digester, or bioreactor, playing a major role in digestion and nutrient supply, as microorganisms do in ruminants (Tacon et al. 2000).

Not surprisingly, chemical analysis of the floc harvested from these culture systems reveals a composition and nutrient profile similar to that of similar flocs taken from domestic wastewater "activated sludge" treatment facilities (McIntosh 2000b; McNeil 2000; Tacon and Ferns 1978/1979;

Tacon 1978/1979). Of particular note: the floc is a good source of protein and essential amino acids (amino acids constitute over 25% of the 'floc' by weight), essential n-3 fatty acids, minerals and trace elements, and B vitamins (Table 13). Moreover, apart from serving as a direct source of nutrients to the shrimp, there is evidence that these organisms also exert a positive effect on the shrimp's digestive enzyme activity and gut microflora (Moss et al. 2001a).

Table 13. Reported composition of suspended particulate matter or `microbial floc' collected from experimental zero-water exchange shrimp rearing tanks (values are ranges and means expressed on a dry meal basis) Source: Tacon et al. (2002).

Nutrient	Range	Mean
Suspended microbial floc (mg/l)	87.3 - 200.8	157
Moisture (%)	5.9 – 7.3	6.6
Crude protein (N x 6.25) (%)	29.2 – 34.3	31.2
Crude lipid (%)	2.5 – 2.6	2.6
Cholesterol (mg/kg)	470 – 490	480
Ash (%)	25.5 – 31.8	28.2
Gross energy (MJ/kg)	10.3 – 12.8	12
Minerals		
Sodium (%)	0.41 – 4.31	2.75
Calcium (%)	0.56 – 2.86	1.70
Phosphorus (%)	0.36 – 2.12	1.35
Potassium (%)	0.13 – 0.89	0.64
Magnesium (%)	0.12 – 0.45	0.26
Zinc (mg/kg)	78.3 – 577.9	338
Iron (mg/kg)	170.8 – 521.0	320
Manganese (mg/kg)	8.9 – 46.8	28.5
Boron (mg/kg)	8.8 – 45.7	27.3
Copper (mg/kg)	3.8 – 88.6	22.8
Essential amino acids		
Methionine + Cystine (%)	0.86 – 0.93	0.89
Phenylalanine + Tyrosine (%)	2.41 – 2.54	2.48
Isoleucine (%)	1.21 – 1.26	1.24
Leucine (%)	1.78 – 1.97	1.87
Histidine (%)	0.43 – 0.45	0.44
Threonine (%)	1.44 – 1.50	1.47
Lysine (%)	0.90 – 0.96	0.93
Valine (%)	1.66 – 1.80	1.73
Arginine (%)	1.46 – 1.63	1.54
Tryptophan (%)	0.18 – 0.22	0.20
Total essential amino acids	24.5 – 26.3	25.4

Apart from offering increased biosecurity (Bullis and Pruder 2000) and markedly reduced water use (Boyd 2000a, 2000b), the most promising feature of zero-water-exchange culture systems is that they offer the possibility of reducing feed costs. The resident floc in these systems contributes substantially to the overall nutritional budget of the cultured shrimp (Table 13), allowing key dietary nutrients such as proteins (including fish meal) and vitamins in compound aquafeeds to be reduced (Chamberlain and Hopkins 1994; Lawrence et al. 1998a; McIntosh 2000b; Tacon 2000b; Velasco and Lawrence 2000a; Velasco et al. 1998; Velasco et al. 2000). For example, McIntosh (2000b) reported that the dietary crude protein level could be decreased from 31% to 24% (with FCR decreasing from 2.2 to 2.0) and body N retention efficiency increased from 23% to 37% in shrimp (*P. vannamei*) reared under commercial zero-water-exchange culture conditions. Clearly, zero-water-exchange culture systems offer considerable promise in moving the shrimp farming community along a path of greater sustainability and environmental compatibility.

Thus, we conclude that particular attention must be given to the further development and/or improvement of on-farm water management techniques aimed at maximizing the growth and effectiveness of aquaculturally beneficial micro-organisms (while avoiding negatively affecting the growth and health of the cultured shrimp). Specific steps include the following.

- Developing better water oxygenation, water circulation/exchange, and water management techniques, including water quality monitoring (Anon 1996a, 1996b; Avnimelech 1999, 2000c; Boyd 2000a, 2000b; Briggs and Funge-Smith 1996; Browdy et al. 1995; Browdy et al. 2001; Chamberlain and Hopkins 1994; Chien, 1992; Conquest et al. 1998; Holloway et al., 1998; Limsuwan 1994; Martinez-Cordova et al. 1998b; Negret 2001; Sandifer et al. 1996; Velasco and Lawrence 2000b; Ziemann et al. 1998).
- Creating better pond and tank designs for raising shrimp and for effluent treatment, including biological filtration (Horowitz et al. 1998; Kim 2000; Losordo et al. 2001; Limsuwan 1996; Moss et al. 2001a; Ogle and Lotz 2000 2001; Pruder et al. 1992; Samocha et al. 2001a; Turk et al. 1998; Van Wyk 2000).
- Improving nutrient management techniques, including fertilization techniques, substrate enhancement, soil/benthos management, and integrated shrimp farming/polyculture techniques (Akiyama and Anggawati 1998; Al Ameeri and Cruz 1998; Allan et al. 1995; Anon, 1993b; Binh et al. 1997; Bratvold and Browdy 2001; Browdy and Bratvold 1999; Daniels 1998; Horowitz and Horowitz 2000d; Jakob et al. 1993; Lee et al. 1996; McNeil 2000; Mitra and Patra 2001; Monroy and Peterson 2001; Nelson et al. 2001; Neeori and Shpigel 1999; Peterson 2000; Queiroz 1998; Samocha et al. 2001b; Scott 2001; Shpigel et al. 2001; Yamasaki and Hirata 1997; Yarish et al. 2000).

Although the bulk of the studies reported to date have been conducted within the Americas with *P. vannamei*, it is expected that such systems would have even greater success within the Asian region, where ponds are generally much smaller and therefore would be more easily managed. In fact, excellent results were reported by French research scientists in Tahiti using zero-water exchange floc-based production systems with *P. japonicus, P. monodon and P. stylirostris* despite their more carnivorous feeding habits (Dr. Gerard Cuzon, personal communication, July 2001).

Challenge 11

- Aquaculture feed manufacturers and shrimp farmers must develop regional, national, or international guidelines and codes of practices for both feed manufacturing practices and feed management practices.

As farming systems intensify and the requirement for the provision of externally supplied aquafeeds increases, there is a need to ensure that aquafeeds are prepared and managed according to certain basic minimum norms and standards. The aim of these standards would be to ensure that the prepared feeds are of an acceptable quality for the target species and farming system on the one hand, and are also managed efficiently on-farm so as to maximize shrimp growth and minimize any negative environmental effects, ultimately ensuring that the consumer receives a safe and wholesome product.

The FAO has recently produced technical guidelines for good aquaculture feed manufacturing practices (FAO 2001b), providing detailed support for Article 9 of the Code of Conduct for Responsible Fisheries (CCRF) on aquaculture development (FAO 1997), in particular, Article 9.4.3 of the CCRF, on the selection and use of feeds and additives. The guidelines deal with the manufacture of industrially compounded aquafeeds, and cover a range of issues, including ingredient purchasing, processing, bulk storage, handling, monitoring, and documentation; as well as employee training and safety, customer relations, and the delivery of finished goods to the farmer. The main objective of the guidelines is to encourage adherence to Good Manufacturing Practices during the procurement, handling, storage, processing and distribution of compound aquaculture feeds or any aquafeeds for farmed finfish and crustaceans. The guidelines by FAO (2001b) included the following points:

- Feed millers must recognize their responsibility to provide high-quality products to their customers, and their intent should be to provide products of consistent quality by implementing sound quality control procedures.
- Ensuring quality is a direct responsibility of all feed mill employees, and each will be held accountable for following accepted procedures designed to implement effective Good Manufacturing Practices for the production of manufactured aquaculture feeds.
- Good aquafeeds can be made only from high-quality feed ingredients; thus, inferior, spoiled, or otherwise damaged or contaminated ingredients must be avoided. The protection of both human and animal health is also prime considerations in the production of effective cost-effective aquafeeds.
- Training and technical assistance are vital to allow both new and experienced employees to handle tasks and solve problems in a manner that ensures the manufacture of consistently high quality feed products. Each mill employee should expend the effort necessary to implement this program because quality assurance is vital to the effectiveness of the aquafeeds being manufactured and to the company's success.
- It is also the feed miller's responsibility to teach the farmer, through label instructions and technical literature and instruction, the correct methods of handling and applying aquafeed for particular species and farming systems.
- The feed manufacturer should clearly state its commitment to its customers and employees to implement good manufacturing practices and carry out an on-going program to improve feed product performance and minimize environmental impacts.
- To the extent practicable, the feed manufacturer should work with farmers not only to enhance production but also to improve aquacultural practices that may have adverse environmental or other impacts.

At present no guidelines exist concerning good on-farm feed manufacturing practice (for use for resource poor or small-scale shrimp farmers) nor concerning good on-farm feed management practices. With regard to the latter, it is important to stress here the important role and responsibility of the shrimp feed manufacturer concerning the provision of adequate information and technical support to their customers (i.e. the farmers) concerning on-farm feed management and use, including adequate record keeping (Davis 2001; Suresh and Zendejas 2000; Tacon and Forster 2000). For addition information and guidelines on existing national/regional norms and standards concerning shrimp feeds and their use, see Boonyaratpalin and Chittiwan (1999; Thailand), Boyd (1999b; Global Aquaculture Alliance), Donovan (1997; Australia), Hamper (2001; Texas, USA) and Tookwinas et al. (2000, 2001; Thailand).

Concluding Remarks

Shrimp farming, like any other farming activity, is a chain of linked processes, in which nutrition and feed management represent only one important link (Wyban and Sweeney 1991). Other equally important links include health and disease management, genetics and stock management (including reproduction), water quality and water use minimization, and (last but not least) the farmer and overall farm management. It follows, therefore, that, the strength and ultimate performance of a shrimp farming activity will be only as good as the weakest link. Clearly, nutrition and feeding cannot be looked at in isolation but rather must be managed more holistically in concert with the other equally important links in the chain.

Finally, the role of government in providing an enabling economic legislative environment for the sustainable and responsible development of the shrimp aquaculture sector cannot be overstated. In particular, there is an urgent need for increased collaboration within and between private and public sector organizations engaged in shrimp aquaculture development activities (at both national and regional/international levels), including research addressing shrimp aquafeed manufacture and pure and applied nutrition (Tacon and Barg 2001; Moss et al. 2001b).

The following is a summary of the main findings of this paper.

Enviornmental Implications and Trends of Feed use in Shrimp Aquaculture

- The shrimp farming sector currently consumes 470,386 MT of fish meal and 36,184 MT of fish oil within compound aquafeeds (dry basis) or the equivalent of 2,351,930 MT of fish (pelagic fish live weight equivalent) for the total global production of 1,130,737 MT of farmed shrimp in 1999; this is equivalent to the consumption of 2.08 kg of fish for every 1.0 kg of shrimp produced.
- The mean fish meal and fish oil content of shrimp aquafeeds in 1999 was estimated to be 26% and 2%, respectively.
- The mean food conversion efficiency of shrimp aquafeeds was 2.0 in 1999, with 2.0 kg of shrimp feed (dry basis) being consumed for each 1.0 kg of shrimp biomass harvested (wet basis). This feed efficiency is equivalent to a shrimp nutrient utilization efficiency of about 25% the remainder being lost to the surrounding aquatic environment.
- At present the majority of shrimp aquafeeds used by farmers are nutritionally over-formulated as complete diets irrespective of the farming system and shrimp stocking density employed and natural food available.
- At present no practical guidelines exist concerning good on-farm feed manufacture and on-farm feed management practices.

Identification of Feeding Practices that Reduce Environmental Impacts

- Replacement of fish meal and fish oil in shrimp aquafeeds with alternative more sustainable feed-grade plant/animal protein and lipid sources.
- Replacement of fresh food organisms in aquafeeds with processed feed materials and processed agricultural by-products.
- Development of improved shrimp feed formulation programs and on-farm feed management practices that take advantage of natural food availability, and by so doing reduce existing dietary nutrient levels and consequent feed wastage.
- Development of improved feed manufacturing technology to produce more water-stable shrimp feeds, and minimizes nutrient loss through leaching and feed disintegration.
- Development of technical guidelines for good on-farm feed manufacturing practices and feed management practices for use by small-scale and large-scale producers.

Constraints and Opportunities for Promoting Such Feeding Practices

- Replacement of fish meal and fish oil within shrimp aquafeeds with alternative protein and lipid sources can only be achieved if changes are made in the basic shrimp culturing practice, such as closing the farming system through water recycling or zero-water exchange, and by maximizing in-situ "floc" and natural food production within the culture system. The upshot of such production systems is that imports of high quality feed ingredients and aquafeeds can eventually be eliminated, and the utilization of locally available agricultural waste streams and by-products greatly improved and maximized.
- The promotion of closed shrimp production systems would greatly reduce water use and increase shrimp production per unit area, but would necessitate the continuous provision of an electricity for aeration during production. Alternative energy sources such as solar might be used, and resource-poor farming communities should also explore wind energy for use.

Suggested Follow-up Activities

- A series of training courses/workshops be implemented within the different major shrimp producing regions to promote awareness in latest developments in shrimp nutrition and feed technology, including the food and feeding of shrimp within closed zero-water exchange culture systems.
- Selected progressive shrimp farmers and major feed manufactures be identified to implement at pilot–scale zero-water exchange culture systems and associated feed management protocols, with emphasis given to the development of farming systems that build on existing infrastructure and expertise rather than simply replacing them with new ones.

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