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Replacement of fish meal in practical diets for the Pacific white shrimp (*Litopenaeus vannamei*) reared under pond conditions

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Abstract

Increasing economical and ecological concerns regarding the use of fish meal in diets for marine shrimp have led to the development of replacement strategies where soybean meal has received ample attention. Most studies evaluating these strategies have been carried out under laboratory conditions which greatly differ from production conditions in ponds. This study evaluated a fish meal replacement strategy using vegetable protein sources in practical feeds for marine shrimp reared in ponds. Juvenile Pacific white shrimp (*Litopenaeus vannamei*) (0.03 g) were stocked into 16 0.1-ha low-water exchange ponds and reared over an 18-week period. Four commercially extruded diets formulated to contain 35% crude protein and 8% lipids were evaluated. These diets included varying levels of fish meal (9, 6, 3, and 0%) which was replaced by a combination of increasing levels of soybean meal (32.5, 34.9, 37.2 and 39.6% respectively) and corn gluten meal (0.0, 1.7, 3.2, and 4.8% respectively) to replace the protein originating from fish meal. At the conclusion of the experimental period, there were no significant differences ($P \geq 0.05$) in shrimp production among the test diets. Mean final yield, final weight, feed conversion ratio and survival values ranged from 5363–6548 kg ha^{-1}, 18.4–20.7 g, 1.38–1.12 and 84.0–94.0%, respectively. Although not significant, as higher levels of plant protein sources were included in the diets, the economic analysis showed a general increase in the partial gross returns of shrimp production. Results from this study demonstrate that fish meal can be completely replaced using alternative vegetable protein sources in practical shrimp feeds without compromising production and economic performance of *L. vannamei* reared in ponds.

Keywords: *Litopenaeus vannamei*; Soybean meal; Fish meal; Plant proteins

1. Introduction

The commercial production of farmed shrimp has been expanding steadily (Josupeit, 2004). According to FAO (2005), 1,804,932 mt (metric tons) of shrimp were cultured in 2003, representing an increase of around 640,000 mt over the production of 2000. This increased production has been accompanied by a decrease in shrimp price, either because of depressed markets or overproduction. As shrimp aquaculture is expected to continue to increase in coming years, shrimp prices are likely to continue to fall as production exceeds demand, therefore challenging the profitability of this industry.

One factor considered to reduce shrimp production costs and increase producers profitability, is the use of feeds with low levels of fish meal and high levels of less expensive, high quality plant protein sources. Commercial shrimp formulations commonly include between 25% and 50% fish meal, representing the primary and most

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expensive protein ingredient. (Dersjant-Li, 2002; Tacon and Barg, 1998; Gonzalez-Rodriguez and Abdo de la Parra, 2004). Fish meal is preferred among other protein sources because it is an excellent source of essential nutrients such as protein and indispensable amino acids, essential fatty acids, cholesterol, vitamins, minerals, attractants and unidentified growth factors (Swick et al., 1995; Samocha et al., 2004). However, limited availability and high demand make fish meal a costly ingredient.

Because of their low price and consistent nutrient composition and supply, plant proteins sources, such as oilseeds, are often economically and nutritionally valuable alternatives to fish meal. Among plant protein sources, soybean meal has received considerable attention in the replacement of fish meal in aquatic animal feeds because of its balanced amino acid profile, consistent composition, worldwide availability and lower price (Akiyama, 1988; Hardy, 1999; Tacon, 2000; Colvin and Brand, 1977; Lim and Dominy, 1990; Akiyama et al., 1991; Swick et al., 1995; Lim et al., 1998; Divakaran et al., 2000; Samocha et al., 2004). However, when compared to fish meal, soybean meal is characterized by a lower composition of essential amino acids, mainly methionine, lysine and threonine (NRC, 1993), and by its lack of the n-3 marine fatty acids EPA (eicopentaenoic acid) and DHA (docosohexaenoic acid), which are essential for the growth and survival of marine shrimp (Fox et al., 2004). Additionally, only 30–40% of the total phosphorus content is considered to be available for *L. vannamei* (Hertrampf and Piedad-Pascual, 2000; Akiyama et al., 1991).

If the replacement strategy considers shifts in essential nutrients, it also appears that fish meal can be removed from shrimp formulations if suitable alternative sources of protein and lipids are provided to meet the nutritional requirements of the animal (Davis et al., 2004). The use of complementary ingredients is a practice used to obtain a more balanced nutrient profile in the feeds (i.e. essential amino acids, fatty acids) and to increase nutrient utilization and facilitate feed processing (Mendoza et al., 2001; Hernandez et al., 2004; Samocha et al., 2004). Davis and Arnold (2000), reported that up to 80% of the fish meal in diets for *L. vannamei* can be substituted by co-extruded soybean poultry by-product meal containing egg supplement or poultry by-product meal without any apparent effect on survival, growth and feed palatability.

Studies evaluating soybean meal and other alternative protein sources to fish meal have often been conducted under controlled laboratory conditions to mitigate the inherent effects of water quality and natural food sources found in shrimp ponds. Although these studies have provided valuable information regarding shrimp capacity to utilize these ingredients under controlled conditions, the practical application of data from these studies is limited. The primary concerns relate to differences in culture environment (e.g. green water ponds vs clear water tanks), length of the growth cycle, and feed processing (extruded vs pelleted) (Tacon, 1996; Moss and Pruder, 1995; D'Abramo and Castell, 1997; Carver et al., 1989; Moss et al., 2001).

In order to effectively transfer technology to the shrimp and feed industries, a logical step would be to carry out studies under conditions similar to those found commercially. This study evaluates fish meal replacement using soybean meal as the main protein source in commercially manufactured feeds for the Pacific white shrimp (*Litopenaeus vannamei*) reared under pond conditions.

2. Materials and methods

2.1. Shrimp source

Post-larval *L. vannamei* (mean weight ± S.D., 1.48 ± 0.39 mg were obtained from Shrimp Improvement Systems, (Plantation Key, FL) and nursed for 19 days in a recirculation system at the Claude Peteet Mariculture Center located in Gulf Shores, Alabama, according to procedures described by Garza de Yta et al. (2004). The nursery system was stocked at a density of 53 post-larvae per liter and water quality parameters maintained at adequate levels for shrimp growth. At the conclusion of the nursery phase, juvenile shrimp (31.2 ± 0.5 mg) were stocked into 16 ponds located in the same facilities, at a density of 35 shrimp per square meter.

2.2. Pond management and water quality

Ponds used for the grow-out phase were 0.1 ha in surface area (46 × 20 m), 1.0 m average depth, and lined with a 1.52 mm thick, high-density polyethylene. Each pond bottom was covered with a 25-cm deep layer of sandy-loam soil and equipped with a 20-cm diameter screened standpipe and a concrete catch basin. Prior to use, pond soils were dried and tilled to allow oxidation and mineralization of organic matter. Two weeks before stocking, ponds were filled with brackish water (9–13 ppt) from the Intracoastal Canal between Mobile and Perdido Bay, Alabama. Inlet water was filtered through a 250-μm nylon filter sock (Micron Domestic Lace Mfg., Inc) in order to prevent the introduction of predators and minimize the introduction of larval species. Inorganic liquid fertilizers were applied

1 week before stocking at a rate of 1697 ml of 32-0-0 (N-P-K) and 303 ml of 10-34-0 (N-P-K) per pond, therefore, providing 5.73 kg of N and 1.03 kg of P_2O_5 ha^{-1}. Two weeks after the first fertilization, a second fertilizer application at half the initial rate was added to ponds with Sechii disk readings greater than 50 cm. Twenty-four hours before stocking, a 1:15 mixture of motor oil and diesel fuel was applied to the pond surface, at a rate of 900 ml per pond, to reduce the number of air breathing insects.

During the experimental period, dissolved oxygen, temperature, salinity and pH concentrations were measured at sunrise (05:00–05:30) and during the evening (20:00–22:00), using a YSI 556MPS meter (Yellow Spring Instrument Co., Yellow Springs, OH, USA). Because of the semi-commercial set up of the production system, evening measurements were carried out in order to optimize aeration and minimize energy consumption. Total ammonia-nitrogen (TAN) and Sechii disk readings were determined on a weekly basis. Water samples for TAN analysis were taken at 40 cm from the pond surface and measured with a spectrophotometer (Spectronic Instrument Inc. Rochester, NY, USA) by the Nesslerization method (APHA, 1989).

In order to maintain minimum dissolved oxygen levels of 3 mg L^{-1}, each pond was provided with a base aeration capacity of 30 hp ha^{-1} (7.5 kW ha^{-1}). Paddle wheel aerators of 1-hp (Little John Aerator, Southern Machine Welding Inc. Quinton, AL) or propeller aspirators aerators of 1-hp (11.2 Ampers) or 2-hp (20 Ampers) (Aire-O_2, Aeration Industries International, Inc. Minneapolis, Minnesota) were used for this purpose. When required, additional aeration (up to 30 hp ha^{-1}) was used to maintain adequate DO levels. Dissolved oxygen and temperature stratification within the water column were managed by running the aerators for about 20 min in the late afternoon after the 8th week. Ponds were managed with a minimal water exchange strategy; therefore, there were no regular water exchanges. However, because of heavy rains associated with tropical storms, the water level of the ponds had to be reduced by 20%, twice at different times during the experiment to avoid flooding. Additionally, the week prior to harvest, 30% of the water from the ponds was replaced, in order to reduce the chance of algae crashes and to encourage shrimp molting before harvest.

Table 1
Ingredient composition of practical diets for *L. vannamei*, used for the replacement of fish meal (FM) with plant protein sources (values expressed on an as fed basis, g/100 g)

Ingredient	9% FM	6% FM	3% FM	0% FM
Soybean meal	32.48	34.82	37.17	39.52
Fish meal — Menhaden	9.00	6.00	3.00	–
Poultry by-product meal	16.00	16.00	16.00	16.00
Milo	35.47	33.82	32.33	30.68
Corn gluten	–	1.67	3.17	4.84
Fish oil	3.96	4.22	4.47	4.72
Di-calcium phosphate	1.50	1.88	2.27	2.65
Bentonite	1.00	1.00	1.00	1.00
Mold inhibitor	0.15	0.15	0.15	0.15
Vitamin premix	0.34	0.34	0.34	0.34
Mineral premix	0.08	0.08	0.08	0.08
Stay-C 35%	0.02	0.02	0.02	0.02

Diets were commercially manufactured by Rangen® Inc. (Angleton, TX) using extrusion processing.

Table 2
Nutritional composition of practical diets for *L. vannamei*, used for the replacement of fish meal (FM)[1] (values expressed on an as fed basis)

Component	9% FM	6% FM	3% FM	0% FM
Crude protein	35.7	35.9	36.2	36.6
Crude fat	8.4	8.3	8.6	8.4
Crude fiber	2.4	1.8	2.1	1.9
Ash	8.2	7.9	7.9	8.1
Calcium[2]	1.3	1.3	1.2	1.1
Total phosphorus[2]	1.2	1.2	1.2	1.3
Lysine[2]	2.0	2.0	1.9	1.8
Met+Cys[2]	1.1	1.1	1.1	1.1
% Protein from plant sources[2,3]	54.9	60.4	66.0	71.5
% Protein from animal sources[2,4]	45.1	39.6	34.0	28.5

[1] Analyzed value — New Jersey Feed Laboratory, Inc. Trenton, NJ.
[2] Calculated value.
[3] Soybean meal, corn gluten meal, milo.
[4] Fish meal, poultry by-product meal.

2.3. Feed formulation strategy and feed management

Shrimp ponds were randomly assigned to one of four dietary treatments, with four replicates per treatment. The basic guideline for the formulation of the diets was to reduce the inclusion of menhaden fish meal (FM) as follows: 9%, 6%, 3% and 0% FM of the total diet, while increasing the inclusion of vegetable protein sources, mainly solvent extracted soybean meal (Table 1). The dietary treatments were formulated in order to provide equal protein and lipid levels while maintaining a minimum lysine and methionine plus cysteine content of 5% and 3% of the total protein, respectively (Table 2). Corn gluten meal was used as a natural source of methionine. Lipid levels were adjusted by adding menhaden fish oil. Calcium phosphate was added to ensure adequate phosphorus supply as fish meal was removed. Feeds were produced by Rangen, Inc.

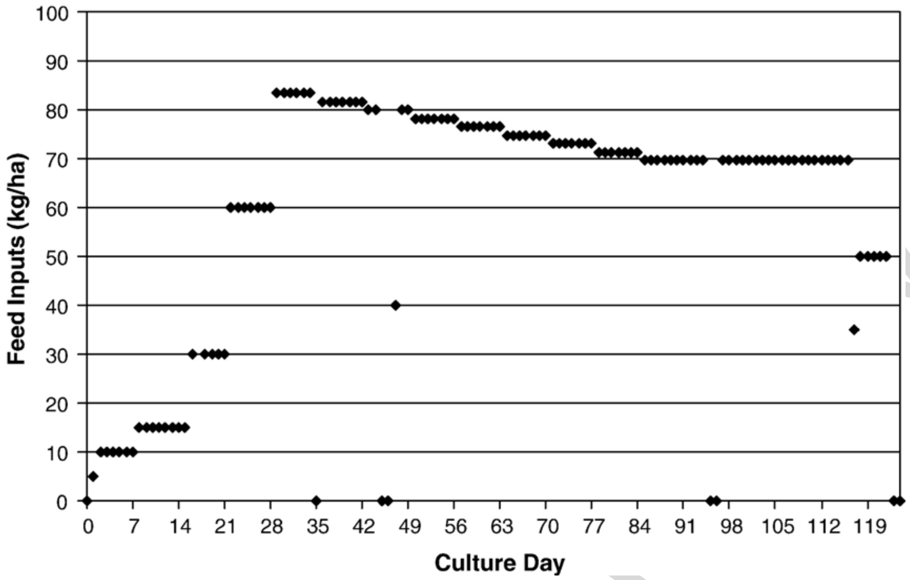

Fig. 1. Daily feed inputs (kg/ha/day) for *L. vannamei*, raised in ponds at a density of 35 shrimp/m^2 over 19 weeks and fed four practical diets with varying levels of fish meal and plant protein sources.

(Angleton TX, USA) under commercial manufacturing conditions and offered twice a day to the shrimp, as a sinkable, extruded 3 mm pellet.

Feed inputs during the 1st, 2nd, 3rd and 4th weeks of pond culture were set at 10, 15, 30 and 60 kg of feed ha^{-1} day^{-1}, respectively. For the remainder of the growth trial, feed inputs were back-calculated, based on an expected weight gain of 1.5 g per week, a feed conversion of 1.2:1, and a total mortality of 30% (1.66% week^{-1}) over an 18-week culture period. Feeding during the first 19 days after stocking was done using the same commercial 35% CP Rangen feed that had been used at the end of the nursery phase. Treatment feeds were offered from day 20, when it was estimated that shrimp had reached 1 g. Maximum feed inputs were set at 83.3 kg of feed ha^{-1} per day during the 5th week (Fig. 1).

Shrimp growth was monitored on a weekly basis by determining the average weight in a sample from 70 to 100 animals per pond. Sampling was carried out by capturing shrimp by seine during the first 2 weeks and cast net (monofilament net, 1.22 m radius and 0.95 cm opening) for the remaining of the culture period.

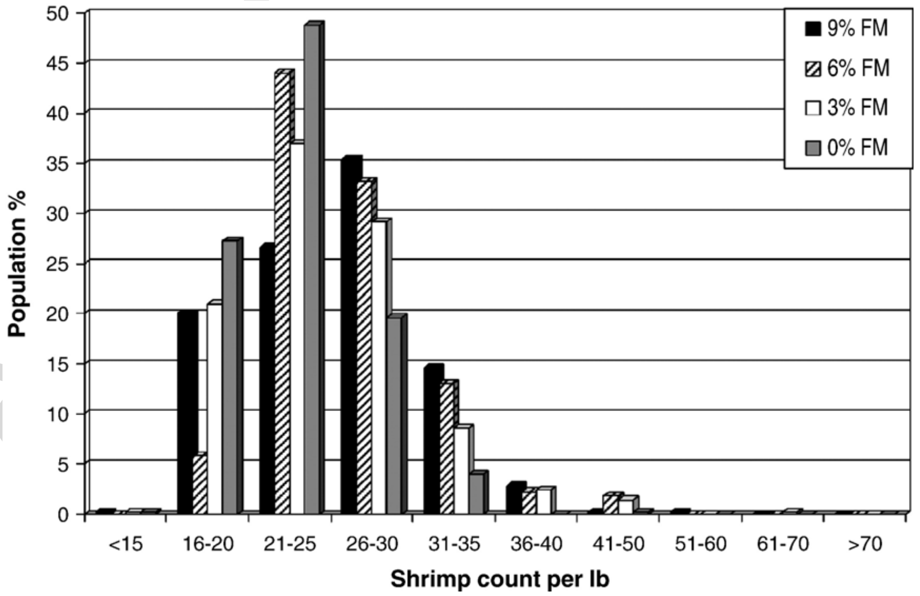

Fig. 2. Size distribution (shrimp count per lb) of *L. vannamei*, fed four practical diets with varying levels of fish meal and raised in ponds for 18 weeks at a density of 35 shrimp/m^2.

Table 3
Summary of water quality parameters observed over an 18-week growing period for *L. vannamei*, fed four practical diets with varying levels of fish meal (FM) and cultured in 0.1-ha ponds

Parameter	9% FM	6% FM	3% FM	0% FM
Dissolved oxygen (mg L^{-1})				
am	4.12±1.64 (0.06, 13.28)	4.09±1.59 (0.13, 11.56)	4.22±1.48 (0.59, 12.83)	4.01±1.58 (0.78, 12.62)
pm	7.25±2.43 (0.97, 16.57)	6.92±2.48 (0.08, 16.80)	7.11±2.42 (0.66, 17.15)	7.31±2.39 (0.82, 16.98)
Temperature (°C)				
am	29.1±1.6 (24.5, 32.9)	29.2±1.6 (24.5, 33.0)	29.1±1.7 (24.5, 32.7)	29.2±1.6 (24.4, 32.7)
pm	30.6±1.6 (25.3, 34.0)	30.7±1.6 (25.1, 34.4)	30.6±1.6 (25.2, 34.0)	30.8±1.7 (24.7, 34.8)
pH				
am	7.61±0.87 (6.16, 9.69)	7.40±0.83 (6.17, 9.62)	7.60±0.87 (6.10, 9.47)	7.41±0.85 (6.12, 10.27)
pm	8.15±0.74 (6.54, 10.04)	8.25±0.77 (6.50, 10.73)	8.41±0.72 (6.87, 9.84)	8.30±0.73 (6.85, 10.02)
Salinity (g L^{-1})				
	9.79±1.2 (7.4, 13.3)	9.62±1.2 (7.4, 13.8)	9.57±1.2 (7.3, 12.9)	8.93±1.3 (5.6, 11.9)
Turbidity (cm)				
	43.7±32.6 (14, 110)	46.1±34.2 (10, 110)	43.6±33.2 (14, 110)	44.5±35.5 (10, 110)
TAN (mg L^{-1})[2]				
	0.77±1.50 (0, 9.33)	1.05±1.68 (0, 7.65)	0.98±1.74 (0, 9.01)	1.15±1.86 (0, 9.88)

Values are mean±standard deviation of daily and weekly determinations. Values in parenthesis represent minimum and maximum readings of the whole data set.

[1] Based on analysis of variance (ANOVA) no significant differences ($P>0.05$) were found among treatment means ($n=4$).

[2] Total Ammonia Nitrogen. Measured once per week.

2.4. Harvest

Following 18 weeks of pond culture, harvest was carried out over a three day period. Feed inputs were stopped 2 days prior to harvesting a given pond. The night before harvest, two thirds of the water from each pond was drained and aeration was provided using paddlewheel aerators to keep shrimp alive and minimize erosion of pond bottoms. Upon harvest, ponds were drained and shrimp pumped from the catch basin using a hydraulic fish pump equipped with a 25-cm diameter suction pipe (Aqualife-Life pump, Magic Valley Heli-arc and Mfg, Twin Falls, Idaho, USA). After pumped, water was drained and shrimp collected in a hauling truck. Shrimp were then transferred to a laboratory located at the same facilities for washing, cleaning and determination of individual weights and final yields (harvested biomass). A random sample of 125 shrimp was collected for individual weight determinations. Individual weights were used to calculate mean final weight, survival and size distributions. After quantifying the biomass from each pond, mean final yield, feed conversion ratio, size distribution (Fig. 2) and survival were determined. Additional economic considerations concerning production and feeding costs were also evaluated.

2.5. Data analysis

Data were analyzed using analysis of variance to determine significant ($P<0.05$) differences among treatment means. The Student–Neuman–Keuls multiple comparison test was used to determine significant

Table 4
Mean production parameters of *L. vannamei,* cultured in 0.1-ha ponds, after 18 weeks of culture and fed four practical diets with varying levels of fish meal (FM) and plant protein sources[1]

Parameter	9% FM	6% FM	3% FM	0% FM	PSE[2]	*P* value
Final weight (g)	19.6	18.4	19.8	20.7	1.39	0.695
Weight gain (%)[3]	62,603	58,635	62,708	67,219	4691	0.652
Final yield (kg shrimp $pond^{-1}$)	584.7	536.3	654.8	634.7	36.1	0.145
Weight gain (g $week^{-1}$)	1.11	1.04	1.13	1.19	0.079	0.695
FCR[4]	1.24	1.38	1.12	1.14	0.078	0.130
Survival (%)	87.2	84.0	94.0	87.4	5.72	0.661

[1] Based on analysis of variance (ANOVA), no significant differences ($P>0.05$) were found among treatment means ($n=4$).

[2] PSE, pooled standard error of treatment means $=\sqrt{\mathrm{mse}/n}$.

[3] Weight gain (%) = 100 × (final weight − initial weight) / initial weight.

[4] Apparent feed conversion ratio = total feed offered / biomass increase.

Table 5
Mean final yield (kg ha^{-1}), divided by size class 468 distribution of head-on shrimp. Prices are based on Gulf fresh shrimp prices between the 13 and 19 of October, 2005[1]

Count of head-on Shrimp per lb	9% FM	6% FM	3% FM	0% FM	USD lb^{-1}
<15	12	–	13	13	$2.00
15–20	1169	311	1375	1726	$1.80
21–25	1555	2360	2423	3097	$1.65
26–30	2070	1781	1912	1244	$1.60
31–35	854	697	563	254	$1.55
36–40	164	118	157	–	$1.50
41–50	12	96	92	13	$1.40
51–60	11	–	–	–	$1.20
61–70	–	–	13	–	$1.10
>70	–	–	–	–	$1.00
Total kg ha^{-1}	5847	5363	6548	6347	

[1] Reported by the National Marine Fisheries Service, Fisheries Statistics Division, Silver Spring, MD, USA.

differences among treatment means (Steel and Torrie, 1980). All statistical analyses were conducted using SAS (V9.1., SAS Institute, Cary, NC, USA).

3. Results

3.1. Pond management and water quality

Prior to stocking of juvenile shrimp in the ponds, Sechii disk readings were measured, with values ranging from 70 to 110 cm. These values were considerably low as compared to readings at stocking from previous research at the same facilities (Venero, 2006; Zelaya, 2005) where they obtained readings between 25 and 85 cm. Low readings at stocking were the result of only having 1 week from fertilization to stocking, as compared to 4 weeks in the other studies. By the 5th week after stocking, it was clear that plankton blooms had completely developed with Sechii disk readings ranging from 25 to 35 cm. Weekly fluctuations in Sechii disk readings were the results of plankton bloom and die-off cycles in the ponds.

Water quality parameters throughout the 18-week experimental period maintained suitable levels for adequate growth and survival of shrimp (Table 3). Analysis of mean values for water quality parameters showed no statistically significant differences among treatments. Specific events of quick reduction in DO concentrations were observed during the second half of the study. These were principally associated to algae die-offs, which subsequently increased TAN concentrations and oxygen demand. Whenever an algae die-off was noticed, two aerators were set to operate continuously for as long as it was required (typically 3–4 days), until a new bloom could develop.

3.2. Production parameters

Feed inputs were modified from the original feeding program when conditions such as low dissolved oxygen levels, risk of storm or lack of electric power to run the aerators were present. Maximum feed inputs were reached at the 5th week of culture, with daily inputs of 83.3 kg ha^{-1}.

At the conclusion of the culture period, there were no significant differences ($P \geq 0.05$) on any of the production parameters evaluated among the test diets. Final weights ranged from 18.4 to 20.7 g and were numerically higher in treatment 4 (0% FM); whereas final yield, FCR and survival were higher in treatment 3 (3% FM) with values ranging for all treatments between 5363 and 6548 kg

Table 6
Mean economic parameters of *L. vannamei*, reared in ponds following 18 weeks of culture and fed four practical diets with varying levels of fish meal (FM) and plant protein sources[1]

Parameter	9% FM	6% FM	3% FM	0% FM	PSE	P value
Final yield (kg ha^{-1})	5847	5363	6548	6347	360.8	0.145
Production value (USD ha^{-1})2	21,134^{a}	19,131^{a}	23,889^{a}	23,445^{a}	1562	0.169
Total feed inputs (kg ha^{-1})	7244^{a}	7232^{a}	7244^{a}	7232^{a}	13.5	0.835
Feed price (USD kg^{-1})3	0.531	0.526	0.52	0.515	–	–
Total feed inputs cost (USD ha^{-1})4	3849^{a}	3802^{b}	3769^{c}	3723^{d}	7.2	<0.0001
Partial gross returns (USD ha^{-1})5	17,285^{a}	15,328^{a}	20,119^{a}	19,722^{a}	1559	0.159

[1] Means ($n=4$) not sharing a common superscript within a row are significantly different ($P<0.05$) based on Student Newman–Keuls multiple range test.
[2] Calculated based on prices and size distributions from Table 5.
[3] Prices on May 2005. Subject to change based on varying ingredients price.
[4] Total feed inputs cost = total feed inputs (kg ha^{-1}) * feed price (USD kg^{-1}).
[5] Partial gross returns = production value (USD ha^{-1}) − total feed inputs cost (USD ha^{-1}).
Estimates are based on shrimp production per hectare[1].

ha^{-1}, 1.12–1.38 and 84%–94%, respectively. Results from this study indicate that feed inputs were adequately assimilated, allowing the shrimp to achieve consistent yields and low feed conversion ratios. Mean productive parameters of *L. vannamei* fed the four dietary treatments at the end of the experimental period are presented in Table 4. High mean survival rates suggest appropriate use of the available food and healthy water quality.

The size distribution of shrimp was determined as it is done commercially, where production is divided by size class, based on the total number of head-on shrimp per lb (453.6 g), with each size class having a differential price. Table 5 provides more detailed information regarding the price for each size class of head-on shrimp (October, 2005), and the final yield (kg ha^{-1}) segmentation for each treatment.

Analysis of economic parameters of the production showed that the total feed inputs cost (total feed inputs (kg ha^{-1}) * feed price (USD kg^{-1})) can be significantly ($P \leq 0.05$) reduced as more plant proteins are included in the diets, with feed price ranging from \$531 (9% FM) to \$515 (0% FM) USD mt^{-1}. On the other hand, there were no statistically significant differences ($P > 0.05$) when the total value of shrimp production (final yields * shrimp prices (Table 5)) and the partial gross returns (production value (USD ha^{-1}) − total feed inputs cost (USD ha^{-1})) data were evaluated. Table 6 summarizes the economic parameters analyzed in this study.

4. Discussion

Commercial shrimp feeds are commonly reported to include fish meal at levels between 25% and 50% of the total diet (Dersjant-Li, 2002; Tacon and Barg, 1998). However, recent studies have shown that commercial shrimp feeds containing 30–35% crude protein can include levels as low as 7.5–12.5% fish meal without compromising shrimp performance (Fox et al., 2004). In another study, Samocha et al. (2004) did not find significant differences in weight gain, survival and feed efficiency of *L. vannamei* fed 32% CP (crude protein) practical diets, where up to 100% of fish meal was replaced with co-extruded soybean poultry by-product meal with egg supplement. The inclusion of soybean and corn gluten meals for the partial and total replacement of fish meal protein in the present study resulted in no adverse affects on the performance of shrimp. Considering that all the test diets had a fixed level of poultry by-product meal (16%), it can be concluded that up to 71.54% of the dietary protein can be provided by high quality plant protein sources (0% FM feed) in shrimp diets (Table 2). Production results obtained in this study are within the range of commercial shrimp production in semi-intensive production systems. At the same facilities and with similar pond management, these production results were similar to those reported by Venero (2006) and better than those obtained by Zelaya (2005) and Garza de Yta et al. (2004).

One of the options proposed to significantly reduce the production costs of the shrimp industry is to replace fish meal with vegetable protein sources in the formulation, therefore reducing the cost of the feeds. In this study, feed costs were slightly reduced as more plant proteins were included in the formulation (Table 6). Since prices were based on those at the time of the research and fish meal has gone up in price and prices vary from region to region, the cost effectiveness of the feed will change. Hence, conclusion with regards to cost effectiveness should be made on a case by case basis.

When evaluated in terms of the total cost of the feed inputs per treatment, significant differences were found among the treatments, indicating that under the conditions of this study, feeding cost were effectively reduced by increasing the level of plant proteins in the diet (Table 6). On the other hand, there were no significant differences in the partial gross returns obtained when subtracting the total costs of the feed inputs from the total value of the final production. Thus, at current ingredient prices and at the substitution levels evaluated in this study, plant protein substituted for fish meal in a properly formulated and manufactured feed is a cost effective practice.

If production costs are to be reduced, shrimp producers must not only have well balanced diets but they must also feed properly. Overfeeding must be minimized and nutrient loading that goes beyond the assimilation capacity of the culture system should be avoided. In addition, in cases where the animal has the potential of using natural productivity, the producer must take advantage of this capacity to improve FCR. It is generally accepted that besides feed inputs, growth and feed utilization by shrimp reared in minimal water exchange pond systems are influenced by the shrimp's ability to consume microbial organisms produced within the culture system (Velasco and Lawrence, 2000; Tacon et al., 2002). Thus, it is clear that nutrition and feeding of shrimp must be studied under conditions which mimic as closely as possible those of the intended farm production unit and environment (Tacon, 1996).

Likewise, technologies aimed to reach feed and shrimp producers require the delivery of information produced under conditions comparable to those used commercially. In recent years, co-extrusion of feed ingredients has been considered as a reasonable option to improve the nutritional quality of soybean meal when used as a replacement ingredient in laboratory manufactured shrimp feeds (Davis and Arnold, 2000; Mendoza et al., 2001; Samocha et al., 2004). Results from this study are in agreement with these findings, and confirm that commercial extrusion may have an important role in improving the overall nutritional quality of shrimp diets including high levels of plant protein sources.

5. Conclusion

Results from this study demonstrate that in commercially manufactured shrimp feeds, fish meal can be completely removed from the formulation using alternative vegetable protein sources in combination with poultry by-product meal without negatively compromising the production performance and economic returns of *L. vannamei* in semi-intensive shrimp production pond systems. It is likely that the positive response of shrimp fed the replacement feeds, was the result of a combination of adequate feed formulation and manufacture, accurate feed inputs and management of the pond ecosystem and the contribution of natural food organisms to the total food intake. Thus, further studies evaluating the contribution and composition of natural food organisms in pond production systems (nutrient modeling) are recommended to determine if the lack of significant difference in performance indicators is due to a “dampening” effect resultant from extrinsic nutrients and not to the level of fish meal in the diet.

The most important implication from these findings, are that fish meal inclusion in commercial shrimp diets can be considerably minimized, up to a 0%, without affecting animal production, while using alternative ingredients, such as solvent extracted soybean meal and corn gluten meal, as protein sources. Likewise, the optimization on the use of fish meal in shrimp feeds will also result in a reduction on the demand for this limited ingredient while contributing to reduce the pressure on wild fish stocks, used for the production of fish meal.

The increasing use of lower cost plant proteins will allow for an important reduction on the cost of the feeds as costly marine ingredients are removed from the formulations, or at least used at more efficient levels. With decreasing shrimp prices in world markets, the lower costs of fish meal-free feeds would particularly benefit shrimp farmers, as they could take advantage of reduced production costs to increase profits. The use of fish meal-free diets also opens the opportunity for producers to reach new markets that would be willing to pay a higher price, for shrimp fed and produced under conditions that do not represent a threat to wild fish stocks and the environment. However, to reach these specific markets further studies are required to evaluate the potential of *L. vannamei* to utilize plant-based diets without animal origin ingredients, such as the poultry by-product meal and fish oil used in this study diets.

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