



Demonstration of alternative feeds for the Pacific white shrimp, *Litopenaeus vannamei*, reared in low salinity waters of west Alabama

Luke A Roy, André Bordinhon, Daranee Sookying, D Allen Davis, Travis W Brown & Gregory N Whitis

Department of Fisheries and Allied Aquacultures, Auburn University, Alabama, USA

Correspondence: DA Davis, Department of Fisheries and Allied Aquacultures, 203 Swingle Hall, Auburn University, Auburn, AL 36849-5419, USA. E-mail: ddavis@acesag.auburn.edu

Abstract

The replacement of marine proteins with vegetable proteins or terrestrial animal byproducts in aquaculture diets has been gaining momentum. This study examines the viability of replacing fish meal in shrimp production diets with alternative protein sources (combinations of vegetable proteins) in inland low salinity waters of west Alabama. The test diets were formulated to contain 36% protein and 8% lipid. The basal diet contained 10% fish meal. The fish meal was then replaced (on a weight to weight basis) with poultry meal (PM), pea meal or distiller's dried grain with solubles (DDGS). Two separate experiments (laboratory trial and farm trial) were devised to test the efficacy of the diets for *Litopenaeus vannamei* reared in low salinity waters. The laboratory trial was conducted at the E. W. Shell Fisheries Research Station in Auburn, Alabama, USA, whereas the farm trial examined the same diets in an outdoor flow-through system at a low salinity shrimp farm in west Alabama. Results indicate no significant differences in shrimp growth, weight gain, survival or feed conversion ratio among dietary treatments, suggesting that PM, pea meal and DDGS can serve as alternatives to fish meal as a protein source for shrimp reared in low salinity environments.

Keywords: poultry meal, distiller's dried grain with solubles, pea meal, low salinity, fish meal, *Litopenaeus vannamei*

Introduction

Farmers of the Pacific white shrimp *Litopenaeus vannamei* in inland low salinity well waters (LSWW) are

faced with the challenge of rearing animals in less than ideal environments (Saoud, Davis & Rouse 2003; Roy, Davis, Saoud & Henry 2007a, b). Depending on their source, inland LSWW available to culture shrimp can be of varied ionic composition and salinity (Boyd & Thunjai 2003; Saoud *et al.* 2003). Ionic imbalances, which are often found in LSWW, can generally be solved through additions of specific ions (e.g. K and Mg) to culture water (McGraw & Scarpa 2003; Roy *et al.* 2007a). Commercial farmers utilizing inland LSWW are mitigating the problem by increasing levels of K and Mg in their pond waters through the addition of muriate of potash and/or KMag (McNevin, Boyd, Silapajarn & Silapajarn 2004). Unfortunately, adding large amounts of agricultural fertilizers to ponds is an additional expense to inland farmers. Increased production costs, competition from foreign markets and the increasing cost of diesel fuel are additional burdens on farmers.

The cost of feed generally accounts for 50–60% of total production costs and, thus, west Alabama shrimp farmers are interested in reducing feed costs. One strategy to reduce feed costs is by reduction in fish meal with alternative plant and animal protein sources. Fish meal is considered among the most suitable protein sources for shrimp feeds. In spite of its importance, a considerable reduction in the use of fish meal is expected in the near future. Among the chief concerns include limited availability, variable supply and cost. Given the growing demand by animal production industries for fish meal and its limited supply, prices are likely to continue to increase, therefore, restraining future use as the main protein source in shrimp feeds. Likewise, emerging environmental and safety issues associated with the use of

potentially contaminated animal byproducts in animal feeds and the effect of fish meal production from natural fish stocks have also been viewed negatively both by the industry and by the general public. One way to address all these issues is to reduce fish meal in shrimp feeds by replacing it with alternative plant and animal proteins. Such a tactic could also provide an economical opportunity for shrimp producers, as some segments of the market would pay a higher price for a premium shrimp fed and produced under environmentally sound conditions (Davis, Samocha, Bullis, Patnaik, Browdy, Stokes & Atwood 2004; Josupeit 2004; Samocha, Davis, Saoud & DeBault 2004; Amaya, Davis & Rouse 2007a, b).

One way in which fish meal can be reduced in shrimp feeds is by replacing it with poultry meal (PM). Several studies have demonstrated the viability of replacing fish meal with PM in shrimp diets (Davis & Arnold 2000; Amaya *et al.* 2007a). Researchers have also focused on the development of alternatives that effectively replace or minimize the inclusion of animal protein sources in commercial shrimp formulations using plant proteins (Colvin & Brand 1977; Lim & Dominy 1990; Piedad-Pascual, Cruz & Sumalangcay 1990; Hardy 1999; Davis & Arnold 2000; Divakaran, Velasco, Beyer, Forster & Tacon 2000; Conklin 2003; Cheng & Hardy 2004; Samocha *et al.* 2004; Amaya *et al.* 2007a, b). Pea meal is a promising alternative plant protein source for fish (Borgeson, Racz, Wilkie, White & Drew 2006; Schulz, Wickert, Kijora, Ogunji & Rennert 2007) and shrimp feeds (Cruz-Suarez, Ricque-Marie, Tapia-Salazar, McCallum & Hickling 2001; Davis, Arnold & McCallum 2002; Bautista-Teruel, Eusebio & Welsh 2003). Pea meal has a moderate level of protein but it has an amino acid profile that compliments soybean meal resulting in a better balanced amino acid profile. The relatively low price and availability of pea meal makes it an attractive candidate to be utilized in shrimp feeds.

Yet another alternative protein source that can be used in association with soybean meal is distiller's dried grain with solubles (DDGS). Distiller's dried grain with solubles is a co-product of the ethanol distillery industry and has been suggested as a less expensive alternative to soybean meal on a per unit protein basis. Several studies have indicated that DDGS is a promising feed ingredient in several fish species including rainbow trout, channel catfish and tilapia (Tidwell, Webster & Yancey 1990; Webster, Tidwell & Yancey 1991; Webster, Tidwell, Goodgame, Clark & Yancey 1992a, b; Webster, Tidwell, Goodgame

& Johnson 1993; Wu, Rosati & Brown 1996; Cheng & Hardy 2004).

Given the current price considerations as well as social concerns over marine ingredients, there is considerable interest in alternative diet formulations. However, there is very little information with regards to the response of shrimp to diets with limited levels of marine ingredients when reared under low salinity conditions. Consequently, the purpose of this study was to examine the supplementation of fish meal with alternative protein sources in diets for shrimp reared in low salinity waters. In the experimental diets, fish meal was replaced (on a weight-to-weight basis) with PM, pea meal or DDGS and the diets were balanced with respect to crude protein and lipid. Experimental diets were examined in two separate growth trials conducted in the laboratory using reconstituted low salinity water and at a low salinity shrimp farm in west Alabama.

Materials and methods

The present work was conducted at the E.W. Shell Fisheries Center in Auburn, Alabama, USA, using reconstituted low salinity water and at a low salinity shrimp farm in west Alabama. Both experimental trials were conducted in July and August of 2007. The experimental diets were randomly assigned to shrimp in five replicate tanks per treatment in both the laboratory and the farm trial. The experimental diets were formulated to eliminate the inclusion of menhaden fish meal, replacing it on a weight-to-weight basis with PM, pea meal or DDGS (Table 1). These diets were produced by Rangen (Angleton, TX, USA) under commercial manufacturing conditions and offered to the shrimp as a sinking extruded pellet. The diets were formulated to contain 36% protein and 8% lipid (Table 2). In the farm experiment, two commercial shrimp diets were included in the trial for comparison with the test diets. The first reference diet was a 35% protein commercial shrimp feed manufactured by Ziegler (Gardner, PA, USA) and served as a high quality commercial reference. The second reference diet was a 36% protein shrimp production diet produced at a local west Alabama feed mill.

Laboratory trial

Artificial low salinity water was prepared 3 weeks before the commencement of the experiment using well water from the E.W. Shell Fisheries Center mixed

Table 1 Ingredient composition of diets for laboratory and farm trials (g kg⁻¹ dry weight)

Ingredient	Diet 1 (Poultry meal)	Diet 2 (Fish meal)	Diet 3 (Distiller's grain)	Diet 4 (Pea meal)
Soybean meal	551.2	537.1	580.1	580.0
Milo	248.1	261.9	163.4	153.3
Poultry-byproduct	99.9	–	–	–
Menhaden select	–	100.1	–	–
Peas, ground	–	–	–	100.0
Distillers grain	–	–	100.0	–
Corn gluten yellow	–	–	48.3	48.3
Dicalcium phosphate	29.0	29.0	33.8	34.2
Fish oil	50.8	50.9	48.3	58.2
Lecithin	5.0	5.0	5.0	5.0
Bentonite	15.0	15.0	15.0	15.0
Squid meal	–	–	5.0	5.0
Vitamin premix*	3.3	3.3	3.3	3.3
Mould inhibitor, Myco	1.5	1.5	1.5	1.5
Mineral premix*	0.8	0.9	0.9	0.9
Stay-C 35%	0.2	0.2	0.2	0.2
Copper sulfate	0.1	0.1	0.1	0.1

Diets were formulated to contain 36% protein and 8% lipid. Diets were commercially manufactured by Rangen[®] (Angleton, TX, USA) using extrusion processing.

*Vitamin premix and mineral premix are proprietary products, thus their composition is not listed.

with an artificial sea salt. A 2500 L recirculating system with tanks connected to a common biofilter was utilized for conducting the growth trial. After the system was filled with well water (0.1 ppt) from the E. W. Shell Fisheries station, 3.9 ppt reconstituted seawater (Crystal Sea Salt, Baltimore, MD, USA) was added to make the final salinity 4.0 ppt (Table 3). Twelve *L. vannamei* juveniles (0.60 g initial weight), were stocked into each tank (four diets with five replicates per diet) of the recirculating system. Ration was calculated assuming a 1.75 feed conversion ratio (FCR) and a doubling in size (approximately every 7 days) until the estimated shrimp weight was in excess of 1 g. Thereafter, a growth rate of 1 g week⁻¹ was assumed. Shrimp were fed four times daily using automatic feeders. On day 43 of the experiment, the shrimp in each tank were harvested, counted and group weighed. Missing shrimp were then replaced with fin-clipped shrimp to equalize the numbers. The shrimp were then harvested again after 10 weeks. At this time, the fin-clipped shrimp were not included in the performance calculations. Mean final weight, biomass, weight gain (%), FCR and survival were assessed at the end of the trial. Dissolved oxygen

Table 2 Proximate and amino acid profile of the four formulated diets

Nutrient	Diet 1 (Poultry meal)	Diet 2 (Fish meal)	Diet 3 (Distillers grain)	Diet 4 (Pea meal)
Moisture (%)	8.85	8.11	8.43	8.43
Protein (%)	35.90	35.50	38.20	36.10
Fat (%)	8.16	8.26	7.66	7.41
Fibre (%)	1.78	1.77	1.95	2.39
Ash (%)	8.40	9.59	6.68	7.90
Amino acid				
Methionine	0.54	0.61	0.62	0.60
Cystine	0.53	0.54	0.62	0.61
Lysine	2.19	2.08	2.18	2.07
Phenylalanine	1.52	1.63	1.71	1.72
Leucine	2.65	2.78	2.91	2.99
Isoleucine	1.47	1.54	1.53	1.53
Threonine	1.31	1.33	1.35	1.34
Valine	1.27	1.33	1.30	1.29
Histidine	0.81	0.87	0.90	0.88
Arginine	2.42	2.41	2.54	2.51
Glycine	1.71	1.91	1.7	1.56
Aspartic acid	3.61	3.8	3.9	3.83
Serine	1.72	1.72	1.82	1.86
Glutamic acid	6.15	6.57	7.40	7.00
Proline	2.03	1.84	2.06	2.06
Hydroxyproline	0.24	0.15	0.15	0.07
Alanine	1.91	1.82	1.86	1.75
Tyrosine	1.08	1.1	1.2	1.21
Total	33.16	34.03	35.75	34.88

Diets were analysed by New Jersey Feed Laboratory, Trenton, NJ, USA.

Table 3 Ionic composition (mg L⁻¹) of low salinity waters used to culture *Litopenaeus vannamei* in the laboratory and farm trial as compared with seawater

Minerals (mg L ⁻¹)	Lab trial	Farm trial	Seawater*
Sodium	1217.4	1635.5	10 500
Potassium	44.1	60	380
Magnesium	156.5	26.1	1350
Calcium	46.4	38.5	400
Salinity (ppt)	4.0	4.0	34.5
Ratios			
Na:K	28.3	27.3	28.3
Ca:K	1.1	0.64	1.1
Mg:Ca	3.4	0.68	3.4

*Goldberg (1963).

(6.4 ± 0.78 mg L⁻¹), temperature (27.8 ± 0.8 °C), pH (8.3 ± 0.1), salinity (4.0 ± 0.0 ppt) were measured daily and remained within acceptable limits. Total ammonia nitrogen (0.013 ± 0.01 mg L⁻¹) and nitrite nitrogen (0.002 ± 0.001 mg L⁻¹) were measured biweekly and also remained within acceptable limits

for the culture of *L. vannamei*. Total ammonia nitrogen was analysed according to Solorzano (1969), whereas nitrite nitrogen was measured according to Parsons, Maita and Lalli (1985).

Farm trial

A series of circular tanks (0.8 m² bottom surface area, 600 L water volume) were set up adjacent to a commercial 4 acre shrimp pond. The water source for the pond is low salinity groundwater with a salinity of 4.0 ppt. In addition, the farmer adds K-mag and muriate of potash to raise K and Mg levels in the pond water to levels adequate for the culture of *L. vannamei* (Table 3). Water from the pond was continuously pumped into the tanks and the overflow drained back into the pond via a central stand-pipe. Water was aerated using submersible diffusers (two per tank) connected to a regenerative blower. Twenty *L. vannamei* juveniles (0.45 g initial weight) were stocked into each of 30 tanks. Each of the four experimental diets and two reference diets were offered to shrimp in five randomly selected tanks. Ration was calculated as was done in the first experiment and shrimp were fed twice daily. Nine weeks after the start of the experiment, all shrimp were harvested, counted and group weighed. Mean final weight, biomass, weight gain (%), survival and FCR were assessed at the end of the trial. A water sample from the supply pond was taken at the start and at the end of the experiment for ion profile analysis (Table 3).

Dissolved oxygen ($7.02 \pm 0.59 \text{ mg L}^{-1}$), temperature ($31.2 \pm 2.4 \text{ }^\circ\text{C}$), pH (8.4 ± 0.3) and salinity (4.0 ± 0.2 ppt) were monitored daily and remained within acceptable ranges for the culture of *L. vannamei*. Ammonia nitrogen ($0.80 \pm 0.41 \text{ mg L}^{-1}$) and nitrite nitrogen ($0.05 \pm 0.05 \text{ mg L}^{-1}$) were measured once weekly. Total ammonia nitrogen was analysed according to Nessler's method (APHA 1989), whereas nitrite nitrogen was measured according to Parsons *et al.* (1985).

Statistical analysis

Statistical analyses were performed using SAS (version 8.2, SAS Institute, Cary, NC, USA). All data were analysed using one-way ANOVA and Student–Newman–Keuls multiple range test to determine if significant differences ($P \leq 0.05$) existed among treatment means (Steel & Torrie 1980).

Results

Laboratory trial

The laboratory trial was conducted without any noticeable problems with water quality or disease occurrences. At the conclusion of the growth trial, there were no significant differences in final weight, biomass, weight gain (%), survival or FCR among shrimp maintained on the various dietary treatments under laboratory conditions (Table 4). Shrimp fed the

Table 4 Initial weight (g), final weight (g), survival (%), weight gain (%), biomass (g) and FCR for *Litopenaeus vannamei* offered diets with alternative protein sources in low salinity water during the lab and farm trials

	Initial weight (g)	Final weight (g)	Biomass (g)	Weight gain (%)	Survival (%)	FCR
Lab trial						
Poultry meal	0.59	8.89 ± 0.45	99.4 ± 6.6	1398.5 ± 115.6	93.3 ± 7.0	2.22 ± 0.12
Fish meal	0.61	9.46 ± 0.42	107.8 ± 13.8	1447.1 ± 96.3	95.0 ± 11.2	2.10 ± 0.16
DDGS	0.61	9.68 ± 0.67	105.8 ± 7.3	1492.7 ± 107.7	91.7 ± 11.8	2.10 ± 0.1
Pea meal	0.63	9.74 ± 0.36	112.9 ± 5.8	1453.7 ± 101.9	96.7 ± 4.6	1.98 ± 0.12
<i>P</i> -value	0.129	0.052	0.160	0.583	0.841	0.059
PSE	0.011	0.24	4.47	52.8	4.56	0.07
Farm trial						
Poultry meal	0.45	24.1 ± 0.71	476.2 ± 32.7	5200.2 ± 147.2	98.0 ± 4.5	0.70 ± 0.02
Fish meal	0.45	24.2 ± 1.0	474.4 ± 29.9	5293.3 ± 310.7	98.0 ± 2.7	0.70 ± 0.03
DDGS	0.45	23.4 ± 1.6	435.1 ± 39.4	5118.0 ± 297.8	93.0 ± 4.5	0.73 ± 0.05
Pea meal	0.45	23.3 ± 0.84	423.2 ± 14.1	5107.3 ± 332.6	91.0 ± 5.5	0.73 ± 0.03
Reference 1	0.46	23.7 ± 1.80	445.3 ± 47.0	5109.7 ± 542.9	94.0 ± 6.5	0.72 ± 0.06
Reference 2	0.44	23.4 ± 0.99	425.8 ± 18.8	5194.1 ± 181.7	91.0 ± 2.2	0.72 ± 0.03
<i>P</i> -value	0.78	0.78	0.049	0.94	0.064	0.81
PSE	0.008	0.61	16.2	164	2.3	0.02

Values represent the mean \pm standard deviation of five replicates. FCR, feed conversion ratio; DDGS, distiller's dried grain with solubles; PSE, pooled standard error.

DDGS and pea meal diets had slightly larger final weights 9.68 and 9.74 g, respectively, compared with PM (8.89 g) and fish meal diets (9.46) but these differences were not significant. Shrimp survival ranged from 91.7% (DDGS treatment) to 96.7% (pea meal treatment). Food conversion ratios ranged from 1.98 to 2.22. Shrimp receiving the PM diet had the highest FCR.

Farm trial

The field trials were also conducted without major system, water quality or disease problems. As in the laboratory trial, there were no significant differences in final weight, weight gain (%), survival or FCR among shrimp offered the various diets under outdoor tank conditions on a commercial farm. While the Student–Newman–Keuls test did not have significant resolution to detect the differences among treatments, biomass was significantly different according to ANOVA ($P = 0.049$). Excellent growth was observed across all treatments with shrimp growing from 0.45 to 23.1–24.2 g in the 9-week culture period. Weight gain (%) was over 5100% across all dietary treatments whereas survival of the shrimp ranged from 91% to 98%. Food conversion ratios were also excellent, ranging from 0.70 to 0.73 across all dietary treatments. The low FCR is presumably due to the high primary productivity of the shrimp pond supplying water to the culture tanks throughout the experimental period. As the farm trial was conducted using green water, it is logical that growth and weight gain (%) would be higher, and FCR would be lower when compared with the laboratory trial which was conducted in a clear water system with no primary productivity and at a lower temperature.

Discussion

Feed is generally the largest expenditure in commercial shrimp operations, and protein is the most expensive component of shrimp feed. West Alabama shrimp farmers are seeking ways to reduce feed costs to increase profitability. Recent efforts aimed at reducing feed costs have resulted in increased use of plant proteins or plant–animal protein combinations in diet formulations as replacements for more expensive fish meal. Results from our study indicate that alternative ingredients (PM, pea meal or DDGS) can be successfully utilized in diets for shrimp reared in low salinity environments without compromising growth and survival. Alternative ingredients were

evaluated under two different conditions, an indoor clearwater recirculating system (lab trial) and an outdoor greenwater system utilizing pond water from a production pond (farm trial).

In both the laboratory and farm trials, no differences in growth, survival, weight gain (%) or FCR were observed among dietary treatments, indicating that shrimp offered well-balanced diets containing PM, pea meal and DDGS performed just as well as shrimp receiving the fish meal diet. A marginal difference in biomass was detected among treatments in the farm trial ($P = 0.049$). These same experimental diets were also offered to shrimp for 12 weeks in outdoor green water systems and 18 weeks in production ponds at near full strength seawater (Sookying, unpublished data) with the same results observed at low salinity. Similar results were observed by Amaya *et al.* (2007b) who found no differences in growth or survival when fish meal (9%, 6%, 3%, 0%) was replaced by poultry-byproduct meal in diets offered to *L. vannamei* reared in a greenwater outdoor tank system. Markey (2007) also observed no differences in production parameters in shrimp reared for 17 weeks in production ponds using different combinations of poultry-byproduct meal (0%, 5%, 10%, 15% poultry-byproduct meal). Davis and Arnold (2000) and Samocha *et al.* (2004) were also successful in replacing fish meal with different varieties or combinations of poultry-byproduct meal.

While PM, in combination with soybean meal, is a plant–animal protein choice for replacement of fish meal, pea meal and DDGS are an all-plant protein alternative. Besides the low cost of ingredients, there are several advantages for choosing an all-plant protein production diet for shrimp. Limited availability, variable supply and detrimental effects on natural fish stocks are a few of the disadvantages of fish meal (Amaya *et al.* 2007a). In addition, emerging environmental and safety issues related to contaminated animal byproducts have been a concern to the industry. The development of all plant protein diets could also provide a niche market for shrimp producers, as some segments of the market are willing to pay a higher price for shrimp produced without the use of animal proteins or byproducts (Davis *et al.* 2004; Josupeit 2004; Samocha *et al.* 2004).

Shrimp offered the diets containing pea meal and DDGS performed just as well as shrimp offered the fish meal and PM diet, which included 5 g kg⁻¹ squid meal as an attractant. Previous studies have also supported the use of pea meal as an alternative protein source for *L. vannamei*. Davis *et al.* (2002) observed

no differences in the growth of *L. vannamei* offered diets containing feed peas after two 7-week growth trials. Bautista-Teruel *et al.* (2003) evaluated feed peas as a protein source for juvenile tiger shrimp, *Penaeus monodon*, and concluded that feed peas could be included at a level of up to 42% in practical diets without any adverse effects on growth, feed intake, FCR or survival. Cruz-Suarez *et al.* (2001) concluded that feed pea meal was an acceptable ingredient in diets for blue shrimp, *Litopenaeus stylirostris*. In addition to shrimp, Schulz *et al.* (2007) and Borgeson *et al.* (2006) determined that peas were also acceptable vegetable protein sources in diets for Nile tilapia *Oreochromis niloticus*. Distiller's dried grain with solubles has been utilized as an alternative protein source in diets offered to a variety of fish species (Tidwell *et al.* 1990; Webster *et al.* 1991, 1992a; Wu *et al.* 1996; Cheng & Hardy 2004). The comparable performance of the shrimp offered the DDGS diet to the fish meal diet would suggest that further investigation of DDGS as an alternative plant protein source for shrimp production diets is warranted.

Results of this study demonstrate that alternative feeds work well under both laboratory and outdoor conditions at low salinity. These results confirm the outcomes of demonstration trials that have been conducted at a number of farms, albeit with limited replication. Given that similar diets have been tested in research ponds (Davis *et al.* 2004; Amaya *et al.* 2007a, b) with suitable replication and good results, commercial producers should be encouraged to evaluate alternative formulations. In most cases, pea meal, poultry-by-product meal and DDGS have been evaluated separately. This study sought to evaluate alternative diets simultaneously using open formulations at low salinity. The economic cost of these feeds is not provided as ingredient prices vary considerably across geographic locations, type of transportation used to move ingredients to the mill, type of purchase (spot, future, etc.), quantity of purchase and quantity contracted across time. Hence, commercial producers are encouraged to evaluate such open formulations under their economic constraint to determine if these types of feeds are economically viable.

Shrimp reared in west Alabama low salinity environments are subjected to suboptimal environmental rearing conditions, namely high Na:K ratios and low levels of aqueous magnesium. These suboptimal conditions have sometimes resulted in poor growth and survival of *L. vannamei* (Saoud *et al.* 2003; McNeven *et al.* 2004; Davis, Saoud, Boyd & Rouse 2005; Roy, Davis & Saoud 2006; Roy *et al.* 2007a) cultured in low

salinity waters. Farmers have expressed concern that removing fish meal from production diets could potentially serve as an additional disadvantage to shrimp reared in low salinity culture systems. Results from this study confirm that fish meal can be removed from production diets without reducing growth and survival of shrimp reared in low salinity waters. Farmers can save money on feed by not including fish meal in their production diets and utilizing plant–animal protein combinations (PM and soybean meal) or all plant protein alternatives such as pea meal or DDGS.

Acknowledgments

The authors would like to extend their gratitude to the Alabama Agricultural Experiment Foundation for providing funds for this study. Thanks also to Nelson Sansing and J. Caleb Hairgrove for technical assistance with this study. The mention of trademarks or proprietary products does not constitute an endorsement of the product by Auburn University and does not imply its approval to the exclusion of other products that may also be suitable.

References

- Amaya E.A., Davis D.A. & Rouse D.B. (2007a) Alternative diets for the Pacific white shrimp (*Litopenaeus vannamei*). *Aquaculture* **262**, 419–425.
- Amaya E.A., Davis D.A. & Rouse D.B. (2007b) Replacement of fish meal in practical diets for the Pacific white shrimp (*Litopenaeus vannamei*) reared under pond conditions. *Aquaculture* **262**, 393–401.
- APHA (American Public Health Association), American Water Works Association, and Water Pollution Control Association. (1989) *Standards Methods for the Examination of Water and Waste Water*, 17th edn. American Public Health Association, Washington, DC, USA.
- Bautista-Teruel M.N., Eusebio P.S. & Welsh T.P. (2003) Utilization of feed pea, *Pisum sativum*, meal as a protein source in practical diets for juvenile tiger shrimp, *Penaeus monodon*. *Aquaculture* **225**, 121–131.
- Borgeson T.L., Racz V.J., Wilkie D.C., White L.J. & Drew M.D. (2006) Effect of replacing fishmeal and oil with simple or complex mixtures of vegetable ingredients in diets fed to Nile tilapia (*Oreochromis niloticus*). *Aquaculture Nutrition* **12**, 141–149.
- Boyd C.E. & Thunjai T. (2003) Concentrations of major ions in waters of inland shrimp farms in China, Ecuador, Thailand, and the United States. *Journal of the World Aquaculture Society* **34**, 524–532.
- Cheng Z.J. & Hardy R.W. (2004) Nutritional value of diets containing distiller's dried grain with solubles for rain-

- bow trout, *Oncorhynchus mykiss*. *Journal of Applied Aquaculture* **15**, 101–113.
- Colvin L.V. & Brand C.W. (1977) The protein requirement of penaeid shrimp at various life-cycle stages in controlled environment systems. *Proceedings of the World Mariculture Society* **8**, 821–840.
- Conklin D.E. (2003) *Use of soybean meal in the diets of marine shrimp*. Technical review paper AQ 144-2003, United Soybean Board and American Soybean Association, Department of Animal Science, University of California, Davis.
- Cruz-Suarez L.E., Ricque-Marie D., Tapia-Salazar M., McCallum I.M. & Hickling D. (2001) Assessment of differently processed feed pea (*Pisum sativum*) meals and canola meal (*Brassica* sp.) in diets for blue shrimp (*Litopenaeus stylirostris*). *Aquaculture* **196**, 87–104.
- Davis D.A. & Arnold C.R. (2000) Replacement of fish meal in practical diets for the Pacific white shrimp, *Litopenaeus vannamei*. *Aquaculture* **185**, 291–298.
- Davis D.A., Arnold C.R. & McCallum I. (2002) Nutritional value of feed peas (*Pisum sativum*) in practical diet formulations for *Litopenaeus vannamei*. *Aquaculture Nutrition* **8**, 87–94.
- Davis D.A., Samocha T.M., Bullis R.A., Patnaik S., Browdy C., Stokes A. & Atwood H. (2004) Practical diets for *Litopenaeus vannamei*, (Boone, 1931): working towards organic and/or all plant production diets. In: *Proceedings Avances en Nutricion Acuicola VII. Memorias del VII Simposium Internacional de Nutricion Acuicola*, 16–19 November 2004, Hermosillo, Sonora, Mexico.
- Davis D.A., Saoud I.P., Boyd C.E. & Rouse D.B. (2005) Effects of potassium, magnesium, and age on growth and survival of *Litopenaeus vannamei* post-larvae reared in inland low salinity well waters in west Alabama. *Journal of the World Aquaculture Society* **36**, 403–406.
- Divakaran S., Velasco M., Beyer E., Forster I. & Tacon A.G.J. (2000) Soybean meal apparent digestibility for *Litopenaeus vannamei*, including a critique of methodology. In: *Proceedings Avances en Nutricion Acuicola V. Memorias del V Simposium Internacional de Nutricion Acuicola*, 19–22 November 2000, Merida, Yucatan, Mexico.
- Goldberg E.D. (1963) The oceans as a chemical system. In: *The Composition of Seawater: Comparative and Descriptive Oceanography. The Sea: Ideas and Observations on Progress in the Study of the Seas* (ed. by M.N. Hill), Vol. 2 (pp. 3–25). Interscience Publisher, New York, NY, USA.
- Hardy R.W. (1999) Alternate protein sources. *Feed Management* **50**, 25–28.
- Josupeit H. (2004) An overview of the world shrimp market. World Shrimp Markets 2004, 26–27 October 2004, Madrid, Spain. <http://www.globefish.org/>
- Lim C. & Dominy W. (1990) Evaluation of soybean meal as a replacement for marine animal protein in diets for shrimp (*Penaeus vannamei*). *Aquaculture* **87**, 53–63.
- Markey J.C. (2007) *Replacement of poultry-by-product meal in production diets for the Pacific white shrimp (Litopenaeus vannamei)*. Master's thesis, Auburn University, Auburn, Alabama, 56pp.
- McGraw J.W. & Scarpa J. (2003) Minimum environmental potassium for survival of Pacific white shrimp *Litopenaeus vannamei* (Boone) in freshwater. *Journal of Shellfish Research* **22**, 263–267.
- McNevin A.A., Boyd C.E., Silapajarn O. & Silapajarn K. (2004) Ionic supplementation of pond waters for inland culture of marine shrimp. *Journal of the World Aquaculture Society* **35**, 460–467.
- Parsons T.R., Maita Y. & Lalli C.M. (1985) *A Manual of Chemical and Biological Methods for Seawater Analysis*. Pergamon Press, New York, NY, USA.
- Piedad-Pascual E., Cruz E.M. & Sumalangcay A. (1990) Supplemental feeding on *Penaeus monodon* juveniles with diets containing various levels of defatted soybean meal. *Aquaculture* **89**, 183–191.
- Roy L.A., Davis D.A. & Saoud I.P. (2006) Effect of lecithin and cholesterol supplemented to practical diets *Litopenaeus vannamei* reared in low salinity water. *Aquaculture* **257**, 446–452.
- Roy L.A., Davis D.A., Saoud I.P. & Henry R.P. (2007a) Effects of varying levels of aqueous potassium and magnesium on survival, growth, and respiration of the Pacific white shrimp, *Litopenaeus vannamei*, reared in low salinity waters. *Aquaculture* **262**, 461–469.
- Roy L.A., Davis D.A., Saoud I.P. & Henry R.P. (2007b) Supplementation of potassium, magnesium, and sodium chloride in practical diets for the Pacific white shrimp, *Litopenaeus vannamei*, reared in low salinity waters. *Aquaculture Nutrition* **13**, 104–113.
- Samocha T., Davis D.A., Saoud I.P. & DeBault K. (2004) Substitution of fish meal by co-extruded soybean poultry by-product meal in practical diets for the Pacific white shrimp, *Litopenaeus vannamei*. *Aquaculture* **231**, 197–203.
- Saoud I.P., Davis D.A. & Rouse D.B. (2003) Suitability studies of inland well waters for *Litopenaeus vannamei* culture. *Aquaculture* **217**, 373–383.
- Schulz C., Wickert M., Kijora C., Ogunji J. & Rennert B. (2007) Evaluation of pea protein isolate as alternative protein source in diets for juvenile tilapia (*Oreochromis niloticus*). *Aquaculture Research* **23**, 537–545.
- Solorzano L. (1969) Determination of ammonia in natural waters by the phenylhypochlorite method. *Limnology and Oceanography* **14**, 799–801.
- Steel R.G.D. & Torrie J.H. (1980) *Principles and Procedures of Statistics: A Biometrical Approach*. McGraw-Hill, New York, NY, USA., 633pp.
- Tidwell J.H., Webster C.D. & Yancey D.H. (1990) Evaluation of distiller's grain with solubles in prepared channel catfish diets. *Transactions of the Kentucky Academy of Science* **52**, 135–138.
- Webster C.J., Tidwell J.H. & Yancey D.H. (1991) Evaluation of distiller's grain with solubles as a protein source in diets for channel catfish. *Aquaculture* **96**, 179–190.
- Webster C.J., Tidwell J.H., Goodgame L.S., Clark J.A. & Yancey D.H. (1992a) Use of soybean meal and distiller's grain with

- solubles as partial or total replacement of fish meal in diets of channel catfish (*Ictalurus punctatus*). *Aquaculture* **106**, 301–309.
- Webster C.J., Tidwell J.H., Goodgame L.S., Clark J.A. & Yancey D.H. (1992b) Winter feeding and growth of channel catfish fed diets containing varying percentages of distiller's grains with solubles as a total replacement of fish meal. *Journal of Applied Aquaculture* **1**, 1–4.
- Webster C.J., Tidwell J.H., Goodgame L.S. & Johnson P.B. (1993) Growth, body composition, and organoleptic evaluation of channel catfish fed diets containing different percentages of distiller's grain with solubles. *Progressive Fish Culturist* **55**, 95–100.
- Wu Y.V., Rosati R.R. & Brown P.B. (1996) Effects of diets containing various levels of protein and ethanol coproducts from corn on growth of tilapia fry. *Journal of Agricultural Food Chemistry* **44**, 1491–1493.