HAYATI Journal of Biosciences 24 (2017) 109–117

Contents lists available at ScienceDirect

HAYATI Journal of Biosciences

journal homepage: http://www.journals.elsevier.com/hayati-journal-of-biosciences

Review paper

Recent Studies Toward the Development of Practical Diets for Shrimp and Their Nutritional Requirements

Christian Larbi Ayisi,[1] Xueming Hua,[1*] Andrews Apraku,[1] Gyamfua Afriyie,[2] Beatrice Amankwah Kyei[3]

[1] Key Laboratory of Freshwater Fishery Germplasm Resources, Ministry of Agriculture, Shanghai Ocean University, Shanghai, 201306, PR China.
[2] Department of Fisheries and Water Resources, School of Natural Resources, University of Energy and Natural Resources, P.O. Box 214, Sunyani, Ghana.
[3] Guangdong Ocean University (GDOU), Xiashan District, Zhanjiang City, 524025 Guangdong Province, PR China.

ARTICLE INFO

Article history:
Received 19 July 2017
Received in revised form
19 September 2017
Accepted 19 September 2017
Available online 12 October 2017

KEYWORDS:
aquaculture,
digestibility,
lipids,
nutrient requirements,
shrimp

ABSTRACT

Shrimp is a very important source of protein which is patronized by almost half of the world's population, and hence a very important specie in aquaculture. There is the need for increase in shrimp production worldwide to meet consumer demands. However, shrimp production is hampered by high cost of commercial feeds. Increase in prices of fish oil and fish meal has led to calls for their substitute. This calls for substitute has resulted in researchers studying the nutritional requirement of shrimp. The rationale for this article is to review the literature available on recent studies toward the development of practical diets for shrimps focusing on the nutrients required by different species qualitatively as well as quantitatively. This review highlights on nutrient requirements with respect to growth and feed utilization. Digestibility of nutrients used in shrimp diets is also accounted for in this article.

1. Introduction

Aquaculture is one of the fastest growing food sectors in the world and one of the prime food producing segments subsequently to agriculture. Shrimp farming is an aquaculture business for the cultivation of marine shrimps or prawns for human consumption, and is now considered as a major economic and food production sector as it is an increasingly important source of protein available for human consumption. Shrimp aquaculture has been growing rapidly with the growth of aquaculture for decades. Among the various branches of aquaculture, shrimp culture has expanded rapidly across the world because of faster growth rate of shrimps, short culture period, high export value, and demand in the market.

Despite the significance of shrimp aquaculture to the global aquaculture production, it faces a lot of challenges including high cost of feed. Shrimp nutrition is extremely important to make a shrimp farm profitable because the cost of the diet exceeds 50% of the variable production cost of a commercial enterprise.

* Corresponding author.
E-mail address: xmhua@shou.edu.cn (X. Hua).
Peer review under responsibility of Institut Pertanian Bogor.

The purpose of this study is therefore to present an update of the nutrient requirements of shrimp.

2. Nutrient Requirements

Because of the large number of species of shrimp being cultured, there seems to be a little or limited information with respect to the nutritional requirement of shrimp although researchers over the past decades have studied extensively on the qualitative as well as quantitative nutrients required by shrimps. In addition to this, is the different requirement by different age groups of shrimps. This section takes a look at the various nutrient requirements of different shrimp species.

2.1. Protein

Protein is the most expensive nutrient in practical diets for shrimp culture of which fish meal (FM) is the most commonly used protein source in the commercial feeds (Oujifard *et al.* 2012). In 2008, shrimp consumed 27.2% of FM used in aquafeeds, making it the largest consumers of FM. Proteins are large, complex molecules made up of various amino acids that are essential components in the structure and functioning of all living organisms.

https://doi.org/10.1016/j.hjb.2017.09.004

Some studies have been conducted to evaluate the effects of different protein levels and sources on shrimp (Bulbul *et al.* 2014; Oujifard *et al.* 2012). For instance, Gauquelin *et al.* in 2007 fed *Litopenaeus stylirostris* (21 g initial weight) six experimental diets with protein ranging from 25% to 58% crude protein (CP) for 50 days. The study revealed that as protein levels increased, weight gain (WG) increased (from 21 to 30 g) and survival rate was averaged as 80%. On the average 1 kJ shrimp^{-1} day^{-1} or 47 kJ kg live weight^{-1} day (22 kJ/kg 0.8 per day), was recorded. In addition, as dietary protein content increased, there was an increase in ammonia production with an O:N ratio indicating that protein was increasingly used as an energy substrate as CP increased.

In an 8-week feeding trial of juvenile white leg shrimp, *Litopenaeus vannamei*, Shahkar *et al.* recorded that the optimal dietary protein level could be 33.4% based on the broken-line analysis of WG for maximum growth performance. Shrimp (1.3 g initial weight) was fed with varying levels of CP at 25%, 30%, 35%, 40%, and 45% in triplicate groups. Growth performance was enhanced linearly and quadratically with an average waste excretion. They therefore recommended that the dietary protein requirement could range between 25% and 33.4%.

Xu and Pan (2014) conducted a study to assess the effects of dietary protein levels on growth, immune, and antioxidant system of shrimp (*L. vannamei*). Four diets with varying protein levels (20%, 25%, 30%, and 35%) were used for the 7-week feeding trial. There was no significant difference in the total hemocyte count in the hemolymph, phagocytic activity of the hemocyte, and antibacterial activity and bacteriolytic activity in the plasma of shrimp. This study documented that the lowest total antioxidant capacity in both the plasma and the hepatopancreas, as well as the lowest reduced glutathione/oxidized glutathione (GSH/GSSG) ratio in the plasma was recorded in shrimp fed with 20% dietary protein. Furthermore, except for the suboptimal growth performance of shrimp in the treatment with 20% dietary protein level, reducing dietary protein level from 35% to 25% would not compromise growth, feed conversion ratio, and physiological status of immune response and antioxidant capability.

In addition, evaluated the performance and dietary cost for the marine shrimp, (*L. vannamei*) using diets with different protein levels. The diets were formulated to contain four varying CP contents of 24.3%, 30.3%, 32.9%, and 36.7%. After 49 days, the highest final WG was recorded in shrimp fed diet with 32.9% CP. This same group recorded the lowest dietary cost.

It is evident that feeding shrimp with diets containing 25%–33% CP will not retard growth performance and feed utilization. However, owing to the numerous species factors such as the age and size of species under consideration, water temperature and salinity as well as culture duration must be taken into consideration.

3. Alternative Sources of Protein

3.1. Alternate protein sources

High digestibility, excellent amino acid and fatty acid profile of FM, makes it an important protein source in shrimp feed and aquaculture feed at large. However, the limited availability and rising costs of dietary FM have resulted in the increasing use of plant proteins and other animal proteins in shrimp and fish feeds (Katya *et al.* 2016; Tacon and Metian 2008). Ideally, these alternative ingredients should have good availability and satisfactory nutritional quality for the species to feed, and also to be economically practical (Goytortúa-Bores *et al.* 2006). Many plant, animal byproducts, and microbial protein sources have already been assessed as possible replacements for FM in feed of shrimp.

3.1.1. Plant protein sources

Because of their low price, availability, and consistence in nutrient composition, plant proteins are normally considered as suitable alternative to FM in shrimp feeds. Over the past decades, aquaculture nutritionists have examined the efficacy of using different plant protein sources in shrimp feeds in place of fish oil. Some of the plant proteins used in shrimp feed are shown in Table 1

Macias-Sancho *et al.* in 2014 assessed the extent to which FM could be partially or fully replaced by *Arthrospira* (*Spirulina platensis*) in diets for *L. vannamei*. In their study, five isonitrogenous diets (~35% protein) were formulated to assess the extent to which FM could be replaced with *S. platensis*. FM was replaced by *S. platensis* at 0%, 25%, 50%, 75%, and 100% and fed to white shrimp (*L. vannamei*) for 50 days with the aim of evaluating the effects on the growth and immunological parameters. The results at the end of the 50 days trial indicated that fish fed diets with 100% *Arthrospira platensis* performed poorer than all other replacement levels. There was a significant difference among the groups with respect to

Table 1. Plant protein sources used in shrimp feed

Plant protein sources	Shrimp species	Observation	Reference
SBMs	Kuruma shrimp, *Marsupenaeus japonicus*	After 56 days feeding trial, *M. japonicus* (1.75 g mean initial body weight), replacing fish oil with soybean meal enhances growth	Bulbul *et al.* 2015
	Juvenile white shrimp, *Litopenaeus vannamei*	After an 8-week feeding trial, it was evident that 20% fish meal could be replaced with extruded soybean meal without compromising growth	Yang *et al.* 2015
	Indian prawn shrimp, *Fenneropenaeus indicus*	After 90 days trial, it is evident that 50% fish meal could be replaced with fermented soybean meal to enhance growth and production, and maximize cost	Sharawya *et al.* 2016
	Speckled shrimp, *Metapenaeus monoceros*	Replacing fish meal with soybean meal up to 40% has no negative effects on growth of shrimp	Rahman *et al.* 2010
CM	Kuruma shrimp, *Marsupenaeus japonicus*	After feeding *M. japonicus* (0.19 g) for 60 days, the report showed that fish meal can be replaced with 20% Canola meal without compromising growth	Bulbul *et al.* 2014
Peanut meal	Pacific white shrimp, *Litopenaeus vannamei*	42 days feeding trial, fish meal can be substituted with 140 g/kg pea nut meal diets for *L. vannamei*	
Rice meal	*Litopenaeus vannamei*	50 days; five isonitrogenous diets (~35% protein), 75% of fishmeal could be replaced by *A. platensis*	Macias-Sancho *et al.* 2014
	Pacific white shrimp, *Litopenaeus vannamei* (Boone)	60 days feeding trial, rice protein can replace fish meal up to 50% in diets for *L. vannamei* without compromising growth	
Sunflower oil cake	Tiger shrimp, *Penaeus monodon*	Sunflower cake can be incorporated into diet of *P. monodon* up to 5% by replacing 20% of fishmeal without affecting growth	Dayal *et al.* 2011

CM = canola meal; SBM = soybean meal.

immunological parameters. The apoptotic index also showed highly significant differences, but only in the group fed a diet consisting of 100% FM replacement. The results showed that up to 75% of FM could be replaced by *A. platensis* without affecting survival or creating a growth depression. Moreover, the smaller substitution level (25%) promoted an enhancement of the tested immunological parameters.

In an attempt to find alternatives to FM, Yang *et al.* (2015) evaluated the replacement of FM with extruded soybean meal (ESBM) in diets of juvenile *L. vannamei*. The authors replaced FM (control diet) at 10% incremental levels of ESBM to have seven experimental diets. The diets were then fed to juvenile shrimp (0.67 g ± 0.01 g mean initial weight) for 8 weeks after which growth and nutrient digestibility of the six diets were determined. The results suggested that replacing FM with ESBM would not affect growth performance, but an upward addition would compromise whole body composition. The lowest CP content of the whole body was significantly lower in shrimp fed diet with 4.28% ESBM ($p < 0.05$) than those fed with 25.26% ESBM, whereas crude lipid content of the whole body of shrimp fed diet with either 16.82% and 25.26% ESBM was significantly higher than those fed with 4.28% ESBM diet ($p < 0.05$). Protein digestibilities of 16.82% and 25.26% ESBM diets were significantly lower than that of the control diet ($p < 0.05$). The authors according to the results inferred that replacing 20% FM with ESBM in the basic diet containing 40% protein and 30% FM is suitable for juvenile *L. vannamei*.

It is worth noting that some studies have been conducted using blend of plant protein sources. Suarezs *et al.* (2009) in a study replaced FM with different plant protein sources and documented that 80% FM can be replaced without compromising growth performance of Pacific white shrimp, *L. vannamei*.

Similarly, Richard *et al.* (2011) documented that replacing 50% of FM with a mixture of plant proteins has the tendency to compromise growth performance of black tiger shrimp. It could therefore be concluded from the above studies as well as Table 1 that FM could be replaced with plant protein sources at different levels without compromising growth, feed utilization, and immune parameters.

3.1.2. Animal protein sources

With respect to animal protein sources, some studies have been conducted as to its impact on growth, feed utilization, and body composition of various species of shrimp.

Table 2 gives a brief summary of alternative animal protein sources used in shrimp feed. Animal protein sources that can be used in shrimp feed includes, meat and bone meal, poultry by-product meal, and porcine meat meal. These animal protein sources are suitable because of their excellent protein content and are relatively cheaper prices.

3.1.3. Microbial protein sources

The use of microbial protein in shrimp feed has gained grounds over the past decades as alternative protein sources (Glencross *et al.* 2007). Despite these advances, recent studies have been difficult because they are unable to provide the necessary long-chain polyunsaturated fatty acids or required short-chain polyunsaturates useful for trophic upgrading (Glencross *et al.* 2007).

In a study by Kun *et al.*, tilapia effluent and sugar were used as growth media to produce microbial flocs in sequencing batch reactors. They then compared two diets without microbial floc with three diets containing microbial flocs over a 35-day period. The control 1 and microbial floc diets (diets 1–3) were formulated with equal levels of CP, total fat, crude fiber, calcium, magnesium, phosphorus, potassium, and sodium. Controls 1 and 2 did not contain microbial flocs and differed slightly from each other in soybean oil, krill meal, and mineral and/or salt levels. For diets 1 and 2, soybean protein isolate on a protein basis was replaced with microbial flocs at a 7.8% and 15.6% inclusion level, respectively, on a dry matter basis. For diet 3, FM was replaced with microbial flocs at 7.8% and fish oil at 0.50%. Four juvenile *L. vannamei* were stocked per tank and each dietary treatment was tested in 12 replicates over a 35-day feeding trial. With respect to WG, shrimp fed diets containing microbial floc performed better compared with the control group.

3.1.4. Carbohydrate

In an FAO training manual (2016), it has been indicated that the third most abundant organic compound in an animal body is carbohydrate (CBH) after protein and lipid. It includes compounds such as sucrose, fructose, glucose, starch, lactose, cellulose, chitin, and glycogen. CBH has been given priority in nutritional studies for its protein-sparing effect because it is one of the principal energetic components which has lower relative cost than protein and lipid. Below are some studies detailing the CBH requirements of different shrimp species.

In an 8-week feeding trial conducted by Hu *et al.* (2009), five practical diets were formulated to contain different levels of lipids (45.86%, 42.01%, 37.82%, 33.30%, and 29.01%) and CBHs (13.82%, 19.41%, 25.72%, 31.80%, and 38.2%, respectively) to check their effect on the growth performance of juvenile shrimp (*L. vannamei*) (mean weight 0.17 ± 0.00 g). No significant difference in growth was observed among the different treatments after the trail. Protein

Table 2. Alternative animal protein sources used in shrimp feed

Alternative animal protein sources	Shrimp species	Observation	Reference
Telescopium mussel meal	*P. monodon*	Feeding trial lasted for 42 days, Fish meal could be replaced up to 100% without negative effects on growth	Kurnia *et al.* 2016
Porcine meat meal	*L. vannamei*	About 35% of fish meal can be replaced by porcine meat meal without affecting growth, survival, FCR, PER, and body composition	Hernández *et al.* 2008
Red crab (*Pleuroncodes planipes*) meal	*L. vannamei*	Red crab meal can be incorporated into shrimp diet up to 15% to enhance growth	Goytortúa-Bores *et al.* 2006
Poultry by-product	*L. vannamei*	Up to 70% of FM can be replaced with poultry by-product without adversely affecting survival, FCR, PER, and body composition	Chi *et al.* 2009
Meat and bone meal	*L. vannamei*	Fish meal can be replaced by meat and bone meal up to 60% without compromising growth, survival, FCR, PER, and body composition	Tan *et al.* 2005
Poultry by-product meal	*M. nipponense*	Fish meal can be replaced by poultry by-product up to 100% for better growth performance	Tan *et al.* 2003
Poultry by-product meal	*P. monodon*	Replacement of fish meal with 80% poultry by-product meal enhanced growth	Xue and Yu, 2005

FCR = feed conversion ratio; FM = fish meal; PER = protein efficiency ratio.

concentration in the intestine of the shrimp was found to be lowest in the group fed the lowest CBH level (13.82%) while muscle glycogen was insignificant. Least values of glucose and protein concentrations in hemolymph were recorded at 13.82% CBH fed to shrimp. As CBH levels were increased, body protein tends to decrease, whereas body lipid and energy showed a reverse. It was therefore concluded that an increased or sufficient amount of CBH greater than 13.82% can have an efficient protein-sparing effect on the shrimp while it was documented that the 13.82% of the CBH cannot satisfy the requirement necessary for good growth performance.

Seven different sources of CBH (wheat starch, sucrose, potato starch, maize starch, dextrin, maltose, and glucose) at the same quantities of 200 g/kg was used to formulate seven experimental diets. Shrimps (*Penaeus monodon*) of initial mean weight 1.92 ± 0.01 g were fed one of the diets for 74 days. Biomass gain (g) and WG (%) were highest in shrimps fed wheat starch or sucrose-containing diet with the lowest occurring in the dextrin-containing diet. Wheat starch-containing diets recorded the highest whole body and muscle protein contents, whereas least values were obtained in the dextrin-containing diets. Dry matter, energy, and apparent digestibility coefficients of protein values were inferior in those fed diets containing dextrin and maize starch. Higher activities of hexokinase and 6-phosphoglyconate dehydrogenase were recorded in those fed wheat starch. *P. monodon* fed wheat starch or sucrose-containing diets recorded higher activities of hepatopancreas amylase. The study indicated that wheat starch or sucrose-containing diets had the best effect on growth performance. It was therefore concluded that these two sources of dietary CBH are more suitable and present same nutritional values in feed for *P. monodon* (Niu *et al.* 2012).

Similarly, juvenile white shrimp (mean weight 8.6 ± 0.5 mg) was fed one of six formulated diets to contain varying levels of corn CBHs (5%, 10%, 15%, 20%, 25%, and 30%) for 42 experimental days. The study was to examine the roles of different levels of diary CBHs on growth performance and ammonia tolerance of the juvenile *L. vannamei* at low salinity level of 3 ppt. Wang *et al.* (2014a,b) indicated that WG and survival was significantly greater than other treatments at 20% while an increase in the whole body crude lipid was obtained as CBH increases. A higher survival rate was obtained in shrimps fed 20% CBH after they were subjected to ammonia challenge for 96 h. The hepatopancreas and muscle glycogen peaked in shrimp fed 15% CBH while other parameters measured showed no significance. The study therefore indicated that a dietary CBH in the range of 15%–20% is optimal for the growth of *L. vannamei* and can enhance its ability to withstand stress at low salinity.

Wang *et al.* (2014a,b) also subjected juvenile *L. vannamei* to low salinity and fed diets containing four ratios of protein to CBH at P26:C30, P30:C25, P34:C19, and P38:C14, respectively, at 3.0 g/L salinity for 8 weeks. The white shrimps were evaluated based on the feed on protein-sparing effects of CBH. WG was observed to be higher in those fed P34:C19 coupled with the highest body protein and lipid. Higher content of hemolymph glucose and R-cell number was obtained in those P30:C25 diet. The values obtained from the study indicated that P30:C25 and P34:C19 supported normal growth of the white shrimp. As such, it was concluded that high dietary CBH to protein ratio can improve growth performance within the range of basic energy demand because the protein-sparing effects occurred in the P30:C25 and P34:19 groups.

3.1.5. Lipids

Lipid is one of the most important components of diet, which serves as the source of available energy and essential fatty acids, forms the major structural components of biomembranes and also acts as carriers of fat soluble vitamins and also functions as precursors of eicosanoids, hormones and enzyme cofactors for the crustacean (Zhao *et al.* 2015).

Fish oil is solely dependent on for the production of feeds for fin and shellfish cultured in captivity. Fish such as herring, sardine, anchovy, and capelin, among others which are of low or no economic value for human consumption are used to produce fish oil. Aquaculture is mostly relying on FM and fish oil (FO) of which Tacon and Metian (2008) reported that aquaculture sector alone consumed approximately 835,000 tons making up about 88.5% of the total fish oil produced in 2006. Generally, the global fish oil production has been overexploited and now endangering some fish species. It was projected that the supply from wild feed grade fisheries will remain static in the next decade; hence, the viability, growth, and profitability of aquaculture could be negatively impacted. Some work has been performed to assess different types of oils as possible use in shrimp feeds in place or with fish oil to cut down the cost of feeding and the cost of aquaculture production at large.

To ascertain the lipid level needed for optimal growth in shrimp, some scientists have studied the impacts of different dietary lipid levels on different species of shrimps with emphasis on growth, survival, food conversion, and production. These include *Macrobrachium rosenbergii* (Felix and Jeyaseelan 2005), *P. monodon*, *Penaeus indicus* (Immanuel *et al.* 2003), *Panulirus cygnus* (Glencross *et al.* 2001), and *L. vannamei* (Zhang *et al.* 2013).

Huang *et al.* evaluated the effects of dietary lipid levels on pacific white shrimp. In their study, they fed pacific white shrimp of initial weight 9.84 ± 0.14 g with diets containing lipids at 4.64%, 6.56%, 8.47%, 10.39%, and 12.31% for 60 days. After 60 days, they documented that fish subjected to 8.47% recorded the maximum WG, least feed conversion ratio, and highest survival rate. Feeding the experimental fish with various levels of lipids had significant effects on fatty acid content of the hepatopancreas and muscle. In addition, the lipid content of these tissues was significantly influenced.

In addition, Zhang *et al.* (2013) evaluated the effects of five isonitrogenous and isoenergetic diets (6%, 8%, 10%, 12%, or 14% lipid) on growth and immunity in white shrimp, *L. vannamei* adults. The authors of this study reported that *L. vannamei* requires different dietary lipid levels at different life stages or growth stages. Twelve percent lipid level proved to be suitable during the first half of the culturing period, but dropped by 2%–10% for the second half of the culturing period. By this, they suggested that dietary lipid levels in the range of 10%–12% enhance growth performance in *L. vannamei*. Interestingly, when the lipid level was increased to 14%, growth was not enhanced and could be attributed to the inability of *L. vannamei* to use the available lipid efficiently.

Recently, Toledo *et al.* (2016) studied the dynamics of dietary lipid levels on *L. vannamei* juveniles (2.87 ± 0.01 g) cultured in biofloc technology. Their prime objective was to assess the influence of different dietary lipid and fatty acids on the nutritional value of bioflocs used as a feed, as well as shrimp performance and health. Three groups of shrimps were fed with one of the three isoprotein experimental diets at different lipid levels (85 g/kg, 95 g/kg, and 105 g/kg). The different diets did not affect water quality after the 61 days of culture. However, they documented that feeding shrimp with different lipid levels could affect survival. Fish fed lower lipid levels had higher survival rates. The total hemocytes count on the other hand was indifferent. They reported that the shrimp showed similar growth and stayed healthy at the end of the experimental period.

The lipid requirements for growing some shrimp species under captive conditions are presented in Table 3.

Table 3. Compilation of published data examining the optimal dietary lipid requirements (expressed on a dry matter basis) of shrimp for maximal growth

Common name	Species name	Initial size (g)/category	Lipid sources	Parameters	Dietary requirements (%)	Reference
White shrimp	*L. vannamei*	3.00	N/A	Growth performance and immune response	10–12	Zhang *et al.* 2013
Indian white shrimp	*F. indicus*	Juvenile	N/A	Growth performance and HUFA retention	14	Ouraji *et al.* 2011
Pacific white shrimp	*P. vannamei*	9.84	FO	WG, FCR, and S	8.47	
White shrimp	*L. vannamei*	0.58	FO and SO	WG, SGR, PER, and FCR	5.98	Wang *et al.* 2014a,b
White shrimp	*L. vannamei*	Brood stock	N/A	HSI, GSI, and WG	8	
White shrimp	*L. vannamei*	0.42–0.56	FO and SO	WG, PER, PI, PPV, and EPV	6	
White shrimp	*L. vannamei*	0.10	FO, SO, and PO	Growth performance	6	Zhou *et al.* 2007

EPV = energy productive value; FCR = feed conversion ratio; FO = fish oil; HSI = hepatosomatic index; PER = protein efficiency ratio; PI = protein intake; PO = peanut oil; PPV = protein productive value; S = survival; SGR = specific growth rate; SO = soybean oil; WG = weight gain; GSI = Gonadosomatic Index; HUFA= Highly unsaturated fatty acid.

3.1.6. Fatty acids

Fatty acids with low melting points are needed at the lower body temperature to support cell membrane flexibility at low water temperatures (Sales and Janssens 2003). It has been documented recently that shrimp can selectively use certain fatty acids for energy by oxidation (Chen *et al.* 2015).

The quality of lipids is dependent on the individual fatty acids the lipids contain. The fatty acid requirements of several shrimp species have been studied and documented. The requirements of essential fatty acid vary among shrimp species. For instance, it has been reported that *P. japonicus* requires four essential fatty acids for optimal growth; linoleic (18:2n-6), linolenic (18:3n-3), Eicosapentanoic acid (EPA) (20:5n-3), and Decosahexanoic acid (DHA) (22:6n-3), and the latter two n-3 Highly unsaturated fatty acid (HUFA) are the most essential (Kanazawa *et al.* 1979). Gonzalez-Felix et al. (2002) documented that *L. vannamei* requires 0.5% of dietary n-3 PUFA for growth.

4. Other Nutrients

4.1. Amino acids

Some studies have assessed the amino acid requirements of shrimp. Dietary threonine requirement by Pacific white shrimp (*L. vannamei*) was examined by Zhou *et al.* using six isonitrogenous and isolipidic diets (43% CP and 7.5% crude lipid, respectively) with graded levels of dietary threonine ranging from 1.07% to 2.30% (dry weight). There was a significant difference observed among all groups with reference to WG. Shrimp subjected to 1.67% dietary threonine recorded the highest mean weight. Addition of dietary threonine beyond 1.67% did not significantly increase WG. This was similar to feed efficiency (FE), protein efficiency ratio (PER), and protein productive values (PPVs). From the results, dry matter, CP, crude lipid, or ash content in the whole body and muscle composition were not significantly altered. The authors therefore used a broken-line model to estimate the optimal dietary threonine requirement based on specific growth rate (SGR) and reported 1.51% of the dry diet (corresponding to 3.53% of dietary protein on a dry-weight basis) as the optimal dietary threonine requirement for *L. vannamei*.

Huang *et al.* fed *L. vannamei* with six isonitrogenous and isolipidic practical diets formulated with graded thiamin levels of 6.9, 32.7, 54.2, 78.1, 145.1, and 301.5 mg/kg of dry diet, respectively. The objective of this study was to assess how the experimental diets would affect growth performance, feed utilization, and nonspecific immune response. Triplicate groups of 30 juvenile shrimps per tank were fed four times a day to apparent satiation. Taking WG and SGR into consideration, dietary thiamin levels had significant influence on the shrimp with the maximal WG and SGR occurred at 54.2 mg/kg dietary thiamin level. Increasing dietary thiamin levels from 54.2 to 301.5 mg/kg led to a significant decline in both WG and SGR. Comparatively, fish diets with thiamin supplemented at 54.2 mg/kg performed better in terms of FE, PER, and PPV than those fed the other diets. Dry matter and protein content in the whole body were significantly affected by the dietary thiamin levels. There was a significant increase in thiamin concentration in hepatopancreas along increasing dietary thiamin supplementation. However, different dietary thiamin levels did not significantly alter total protein, glucose, triacylglycerol, and cholesterol contents in hemolymph. Thus, dietary thiamin supplementation of 44.66 mg/kg would appear to be adequate for maximum growth of juvenile Pacific white shrimp, *L. vannamei* according to the results of the two-slope broken-line model based on WG.

Xia *et al.* (2015) fed juvenile Pacific white shrimp with six isonitrogenous and isolipidic practical diets containing graded niacin levels; 10.9, 65.8, 121.2, 203.4, 387.5, and 769.3 mg/kg of dry diet to evaluate the effects of dietary niacin on growth performance, feed utilization, and nonspecific immune response in juvenile Pacific white shrimp. From the results, the dietary niacin levels had significant influence on WG, SGR, FE, PER, and PPV. Although there were no significant differences in survival and proximate composition of the whole body after the feeding trial, shrimp subjected to 121.2 mg/kg niacin diets had the highest WG and SGR. In addition, the total protein, glucose, triacylglycerol, and cholesterol contents in the hemolymph were indifferent. However, the activity of catalase and lysozyme in the hemolymph were significantly affected by dietary niacin levels. The authors therefore documented that diets with 109.6 mg/kg were the optimal niacin requirement for juvenile Pacific white shrimp following a two-slope regression analysis of SGR against dietary niacin levels.

4.2. Vitamins

For normal growth, reproduction, and optimum health, vitamins are required in small amounts from an exogenous source (usually the diet). In aquatic animal nutrition, vitamins are among the most expensive ingredients used in complete diet formulation (Gaylord *et al.* 1998).

Some studies have been conducted to evaluate the optimal requirements of vitamins in shrimp aquaculture (Nguyen *et al.* 2012; Wen *et al.* 2015). This section takes a look at some of these studies.

Vitamin D_3 is essential in the diets of crustaceans because of its ability to help in the mineralization of exoskeleton through the transportation of absorbed calcium. Vitamin D_3 is important for the development, growth, and maintenance of a healthy skeleton, and also involved in the alkaline phosphatase and calcium-dependent enzyme activity. Despite its essence in shrimp and crustaceans at large, much has not been performed to ascertain the nutritional requirements. Having this as a background, Wen *et al.* (2015) in a 10-week feeding trial evaluated the dietary requirements of vitamin D_3 in juvenile *L. vannamei* cultured at low salinity rearing conditions. Triplicate groups of shrimp *L. vannamei* (initial average weight 0.39 g) were subjected to one of the experimental diets twice daily. The basal practical diet contained 685 IU vitamin D_3 per kg diet, diets 2−6 contained 1960, 3240, 4220, 5630, and 7550 IU vitamin D_3 per kg diet, respectively. The diets did not influence growth performance and alkaline phosphatase activity in liver. Hepatosomatic index of shrimp fed diets containing vitamin D_3 at 685, 1960, and 3240 IU/kg was lower than the diet containing vitamin D_3 at 7550 IU.

The study revealed that vitamin D_3 from ingredients could meet the growth requirement, but not for whole body mineral deposition. 6366 IU/kg was recommended to be the required vitamin D_3 for juvenile *L. vannamei* at low salinity rearing conditions after the broken-line regression had been used for analysis.

Cui *et al.* evaluated the effects of six shrimp diets containing varying levels of vitamin B_6 levels (2.6, 32.7, 54.8, 90.7, 119.6, and 247.4 mg/kg, dry diet) in juvenile Pacific white shrimp, *L. vannamei* (approximately 1.0 g). The feeding trial lasted for 8 weeks and were fed in triplicate groups of 40 juvenile shrimps per tank four times each day to apparent satiation. Feeding diets with different vitamin B_6 levels significantly influenced PER, SGR, FE, WG, and PPV of the shrimp. However, the different diets did not alter the whole body and muscle composition significantly, although dry matter and protein contents in the whole body were different. There was a significant increase in vitamin B_6 concentration in the hepatopancreas with the dietary vitamin B_6 level increasing from 2.6 to 32.7 mg/kg. They then calculated the optimal dietary vitamin B_6 requirements using a two-slope broken-line model based on WG and SGR and an exponential model based on the vitamin B_6 concentration in the hepatopancreas which were 110.39, 110.08, and 167.5 mg/kg, respectively. A summary of the dietary vitamin requirements is given in Table 4

5. Minerals

Owing to the continuous and increase in plant protein utilization in place of FM as well as dynamic nature of most commercial feeds, there is the need for minerals to be incorporated into commercial feeds. Plant protein sources usually contain antagonists such as phytic acid. This product (phytic acid) combines with divalent cationic trace minerals, hence making them unavailable to animals including shrimp (Katya *et al.* 2016).

To enhance growth, increase metabolism, and ensure good health in aquaculture species including shrimp, minerals such as Cu, Zn, Fe, Se, and Mn are of great importance. For instance, Zn is an essential trace mineral, which is essential for biochemical processes such as metabolism of protein, regulation of genes, maintaining healthy bones and cell membranes as well as production of energy, and finally growth (Watanabe *et al.* 1997). Zn deficiency signs such as retarded growth, higher mortality rates, cataract, and low zinc content in tissues are seen when there is less or inadequate zinc in diets of shrimp. However, an excess Zn in the diets of shrimp could prove costly as it may be toxic, thereby the required amount should be administered to avoid deficiencies or toxicity.

Mn is also of great importance in the diet of shrimp because it serves as a cofactor in several enzymatic systems of which includes but not limited to the synthesis of urea from ammonia, metabolism of amino acid and fatty acid as well as the oxidation of glucose (Lall 2002).

Because of the function of copper in hematopoiesis and in numerous Cu-dependent enzymes including lysyl oxidase, cytochrome oxidase, ferroxidase, tyrosinase, and superoxide dismutase, it is said to be an essential trace metal for animals including shrimp. It is important for both molting and reproduction in Pacific white shrimp (*L. vannamei*; Rao and Anjaneyulu 2008). The dietary copper requirements have been estimated to be 32 and 15−21 mg/kg for black tiger shrimp (*P. monodon*) and pacific white shrimp (*L. vannamei*), respectively (Lee and Shiau 2002). In another study by Wang *et al.*, the dietary copper requirement for *Pistacia chinensis* was reported to be 25 mg/kg.

Selenium (Se) is an important nutrient for crustaceans (Watanabe *et al.* 1997). It protects cell membranes against oxidation by catalyzing the reactions needed for the conversion of hydrogen peroxidase and fatty acid into water and fatty acid alcohol using reduced glutathione (Lin and Shiau 2005). Se is both an essential and toxic trace element with narrow margin of tolerance in biological systems. In addition to the regulation of inflammation and immune responses, it has antitumor properties (Köhrle *et al.* 2005).

In Table 5, we give a summary of reports on the dietary mineral requirements of the economically important shrimps.

6. Apparent Digestibility of Feed Nutrients

Some researchers have over the past years conducted studies in relation to the apparent digestibility of nutrients used in shrimp diets (Bautista-Teruel *et al.* 2003; Smith *et al.* 2006; Sudaryono *et al.* 1999; Oujifard *et al.* 2012). In order to formulate diets to meet the prescribed nutrient specifications at least cost, it is essential to have adequate and updated knowledge on the nutrient digestibility of feed ingredients available. For instance, Terrazas-Fierro *et al.* (2010) stated that apparent protein and amino acid digestibility coefficients of feedstuffs are needed for more accurate, environment friendly, and economical feed formulations for shrimp. Feed may not be consumed by the shrimp or fish leading to environmental pollution, although it was formulated using adequate amounts of nutrients. With proper

Table 4. Dietary vitamin requirements by shrimp species

Species	Initial weight (g)	Protein source(s)	Parameter(s)	Dietary vitamin evaluated	Dietary vitamin requirements	Reference
L. vannamei	0.014	N/A	WG, SGR, CF, GOT, and GPT	B_6	106.95−151.92 mg/kg	Li *et al.* 2010
P. monodon	0.84	Vitamin free casein	WG and GOT	B_6	72−89 mg/kg diet	
L. vannamei	0.39	Soybean mean, peanut meal	WG, SGR, FE, PER, and HSI	D_3	6366 IU/kg	Wen *et al.* 2015
L. vannamei	1.0	Fish meal, soybean meal	WG, SGR, and PER	B_6	110.39 mg/kg	
P. muelleri	1.0	Squid mantle (85% crude protein)	Growth, survival, hepatopancreatic cell morphology, and digestive protease activity	A	180 mg/kg	
P. monodon	0.29	Vitamin-free casein (86% crude protein)	WG, SOD, RB, and THC	E (DL-a-tocopheryl acetate, DL-a-TOA)	179 mg/kg	Lee and Shiau, 2003

CF = condition factor; FE = feed efficiency; GOT = Glutamic-oxalacetic transaminase; GPT = Glutamic Pyruvic Transferase; HSI = hepatosomatic index; PER = protein efficiency ratio; RB = Respiratory Burst; SGR = specific growth rate; SOD = superoxide dismutase; THC = total hemocytes count; WG = weight gain.

Table 5. Dietary mineral requirements by shrimp species

Common name	Species name	Initial size (g)/category	Minerals	Parameters	Dietary requirements
Black tiger shrimp	*P. monodon*	2.98	Copper	Immune parameters	22–55 mg/kg
White shrimp	*L. vannamei*	16.73	Copper	Growth, immune parameters	30 mg/kg
White shrimp	*L. vannamei*	0.49	Copper	Growth, muscle, and hepatopancreas Cu accumulation	34.71–58.01 mg/kg
White shrimp	*L. vannamei*	N/A	Potassium	Growth, body composition, immune parameters	0.96–1.26 g/kg
White shrimp	*L. vannamei*	0.41	Selenium	MGR, FCR, SGR, T-OAC, SOD, and MDA	0.84 mg/kg
White leg shrimp	*P. vannamei*	0.01	Phosphorus	Growth and survival	1.2%
White leg shrimp	*P. vannamei*	0.01	Calcium	Growth and survival	0.8%

FCR = feed conversion ratio; MDA = Malondialdehyde; MGR = Muscle Gut Ratio; SGR = specific growth rate; SOD = superoxide dismutase; T-OAC = Total Antioxidant Capacity.

information on the digestibility of nutrients in a particular feed stuff, an effective feed can be prepared at least cost. Therefore, evaluating the nutrient digestibility is the first step in assessing the efficacy of an ingredient to be used in formulating diets for a targeted species. Table 6 gives a summary of the digestibility of some nutrients used in shrimp feed formulation.

7. Conclusion and Recommendation

To maximize feed and ensure optimal growth and performance, the available data show that shrimp generally require 6%–14% dietary lipids in their diet to enhance growth. In addition, the literature available to the best of our knowledge shows that dietary vitamins are of great essence to the growth of shrimp and could be incorporated in their diet between 72 and 180 mg/kg diet with variances in different vitamins. Plant meal could be incorporated in shrimp diets as low as 5% and as high as 75% depending on the source, whereas the incorporation of animal meal ranged between 15% and 100%.

To enhance better understanding of the nutrient requirements and utilization by shrimp, future research or trials should use modern techniques such as "omics" which includes lipomics, metabolomics, and proteomics. These techniques provide holistic picture compared with the single dose–response growth or biochemical methods.

It is evident that studies on the nutritional requirement of shrimp have been skewed toward some species, such as Pacific white shrimp, *L. vannamei*. It is therefore a critical need for a more

Table 6. The dry matter, crude protein, ash, crude lipid, and gross energy composition and apparent digestibility of selected air-dry feed ingredients determined for various shrimp species

Ingredient	Proximate composition					AD coefficients (%)b			Shrimp species	Reference
	DM (%)	Ash (%)	CP (%)	CL (%)	GE	DM	CP	GE		
Marine meals										
Monterrey sardine meal (66.2% CP)	96.5	16.6	66.2	ND	4.6 kcal/g	76.2	84.9	ND	*L. vannamei*	Terrazas-Fierro *et al.* 2010
Tuna by-product meal	95.4	15.8	60.5	ND	5.0 kJ/g	52.6	70.5	ND	*L. vannamei*	Terrazas-Fierro *et al.* 2010
Catarina scallop by-product meal	95.5	22.2	50.2	ND	4.4 kJ/g	67.2	86.8	ND	*L. vannamei*	Terrazas-Fierro *et al.* 2010
Fish soluble protein concentrate	92.0	11.4	79.4	ND	4.8 kJ/g	102.0	99.3	ND	*L. vannamei*	Terrazas-Fierro *et al.* 2010
Red crab meal	95.5	39.1	38.1	ND	3.4 kJ/g	51.6	84.6	ND	*L. vannamei*	Terrazas-Fierro *et al.* 2010
Shrimp head meal	95.3	25.4	49.8	ND	3.9 kJ/g	84.0	98.0	ND	*L. vannamei*	Terrazas-Fierro *et al.* 2010
Squid meal	92.5	17.2	71.2	ND	4.5 kJ/g	95.0	95.4	ND	*L. vannamei*	Terrazas-Fierro *et al.* 2010
Fish meal	926	223	623	58	18.6 MJ/kg	87.0	90.9	97.2	*L. vannamei*	Liu *et al.* 2013
Shrimp head meal	962	453	371	17	12.2 kJ/g	50.5	78.9	63.0	*L. vannamei*	Liu *et al.* 2013
Squid visceral meal	868	66	406	159	20.1 kJ/g	51.6	70.9	66.8	*L. vannamei*	Liu *et al.* 2013
Shrimp byproduct meal	88.89	N/A	49.90	1.88	20.97 kJ/g	52.83	84.71	72.32	*L. vannamei* (Boone)	Yang *et al.* 2009
Fish meal	93.11	N/A	63.07	8.86	21.89 kJ/g	82.78	91.62	86.79	*L. vannamei* (Boone)	Yang *et al.* 2009
Terrestrial plant meals										
Full fat soybean meal	ND	9.6	33.5	13.5	4978 kJ/g	82.7	95.7	88.1	*L. vannamei*	Cruz-Suárez *et al.* 2011
Defatted soybean meal	ND	10.1	38.6	7.3	4632 kJ/g	84.2	96.9	89.3	*L. vannamei*	Cruz-Suárez *et al.* 2011
Soy protein concentrate	ND	10	46.2	5.9	4714 kJ/g	82.6	93.0	85.1	*L. vannamei*	Cruz-Suárez *et al.* 2011
Soy protein isolate	ND	10.3	51	5.7	5026 cal/g	91.7	96.2	98.2	*L. vannamei*	Cruz-Suárez *et al.* 2011
Soybean meal	927	60	474	12	18.2 MJ/kg	71.7	92.3	83.0	*L. vannamei*	Liu *et al.* 2013
Rapeseed meal	912	77	366	30	17.4 kJ/g	50.8	78.3	65.6	*L. vannamei*	Liu *et al.* 2013
Peanut meal	940	129	462	77	18.7 kJ/g	53.2	88.8	72.0	*L. vannamei*	Liu *et al.* 2013
Corn gluten meal	951	17	603	21	20.4 kJ/g	48.6	55.7	51.1	*L. vannamei*	Liu *et al.* 2013
Brewer's yeast	916	48	380	40	18.3 kJ/g	71.7	85.7	84.6	*L. vannamei*	Liu *et al.* 2013
Fermented soybean meal	91.77	N/A	48.76	1.22	21.19 kJ/g	69.98	90.89	74.12	*L. vannamei* (Boone)	Yang *et al.* 2009
Extruded soybean meal	87.72	N/A	45.79	2.82	20.46 kJ/g	71.20	90.8	82.00	*L. vannamei* (Boone)	Yang *et al.* 2009
Soybean meal	90.29	N/A	39.98	17.88	23.13 kJ/g	69.98	88.95	81.39	*L. vannamei* (Boone)	Yang *et al.* 2009
Peanut meal	90.13	N/A	54.50	6.95	21.36 kJ/g	70.00	93.18	82.29	*L. vannamei* (Boone)	Yang *et al.* 2009
Wheat gluten meal	91.32	N/A	74.89	1.81	23.61 kJ/g	76.47	89.32	86.43	*L. vannamei* (Boone)	Yang *et al.* 2009
Corn gluten meal	93.37	N/A	59.79	3.32	23.66 kJ/g	77.10	87.89	86.81	*L. vannamei* (Boone)	Yang *et al.* 2009
Terrestrial animal meals										
Blood meal	931	109	779	7	19.5 kJ/g	55.2	69.1	57.5	*L. vannamei*	
Meat and bone meal	949	216	565	137	20.5 kJ/g	76.5	82.2	82.3	*L. vannamei*	
Meat and bone meal	96.23	N/A	51.53	17.59	22.52 kJ/g	56.33	73.88	84.80	*L. vannamei* (Boone)	Yang *et al.* 2009
Plasma protein meal	93.14	N/A	66.86	1.80	19.68 kJ/g	71.23	92.34	88.16	*L. vannamei* (Boone)	Yang *et al.* 2009
Poultry meat meal	91.07	N/A	64.90	12.60	20.97 kJ/g	68.48	75.00	75.45	*L. vannamei* (Boone)	Yang *et al.* 2009

AD = apparent digestibility; CL = crude lipid; CP = crude protein; DM = dry matter; GE = gross energy.

detailed nutritional study on the unexplored species, although it is expected that the nutritional requirements of the explored species should apply to all other species. In addition, there seems to be a little information on how the different nutrient compositions (experimental diets) affect the genes related to growth and immune response of shrimp. This area could also be explored in future studies.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgement

The authors are grateful to Shanghai Science and Technology Committee (No. 14320502000) for supporting this study financially.

References

Bautista-Teruel MN, Eusebio PS, Welsh TP. 2003. Utilization of feed pea, *Pisum sativum*, meal as a protein source in practical diets for juvenile tiger shrimp, *Penaeus monodon*. *Aquaculture* 225:121–31.
Bulbul M, Kader MA, Ambak MA, Hossain MS, Ishikawa M, Koshio S. 2015. Effects of crystalline amino acids, phytase and fish soluble supplements in improving nutritive values of high plant protein based diets for kuruma shrimp, *Marsupenaeus japonicus*. *Aquaculture* 438:98–104.
Bulbul M, Kader MA, Koshio S, Ishikawa M, Yokoyama S. 2014. Effect of replacing fishmeal with canola meal on growth and nutrient utilization in kuruma shrimp, *Marsupenaeus japonicus*. *Aquac Res* 45:848–58.
Chen K, Li E, Xua C, Wanga X, Lin H, Qinc JG, Chen L. 2015. Evaluation of different lipid sources in diet of pacific white shrimp *Litopenaeus vannamei* at low salinity. *Aquac Rep* 2:163–8.
Chi S, Tan B, Mai K, Zhen S. 2009. Growth and feed efficiency of juvenile shrimp *Litopenaeus vannamei* fed formulated diets containing different levels of poultry by-product meal. *J Ocean Univ China* 8(4):399–403.
Cruz-Suarez LE, Ricque-Marie D, Tapia-Salazar M, McCallum IM, 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.
Dayal SJ, Rajaram V, Ambasankar K, Ahamad Ali S. 2011. Sunflower oil cake as a replacement for fishmeal in feed of tiger shrimp, *Penaeus monodon* reared in tanks in net cages. *Indian J Geo-Mar Sci* 40(3):460–70.
FAO. 2016. The nutrition and feeding of farmed fish and shrimp: A training manual. United Nations: Fisheries and Aquaculture Department, United Nations. http://www.fao.org/docrep/field/003/AB470E/AB470E05.htm.
Felix N, Jeyaseelan MJP. 2005. Influence of dietary lipid to carbohydrate ratios on the growth and food conversion of post larvae of *Macrobrachium rosenbergii* (de Man). *Indian J Fish* 52:55–60.
Gaylord TB, Rawles SD, Gatlin III DM. 1998. Re-evaluation of vitamin E supplementation of practical diets for channel catfish, *Ictalurus punctatus* production. *Aquac Nutr* 4:109–14.
Glencross BD, Booth M, Allan GL. 2007. A feed is only as good as its ingredients - a review of ingredient evaluation for aquaculture feeds. *Aquac Nutr* 13:17–34.
Glencross BD, Smith M, Curnow J, Smith DM, Williams KC. 2001. The dietary protein and lipid requirements of post-puerulus western rock lobster, *Panulirus cygnus*. *Aquaculture* 199:119–29.
Gonzalez-Felix ML, Gatlin DM, Lawrence AL, Perez-Velazquez M. 2002. Effect of dietary phospholipid on essential fatty acid requirements and tissue lipid composition of *Litopenaeus vannamei* juveniles. *Aquaculture* 207:151–67.
Goytortúa-Bores RE, Civera-Cerecedo S, Rocha-Meza A, Green Y. 2006. Partial replacement of red crab (*Pleuroncodes planipes*) meal for fish meal in practical diets for the white shrimp *Litopenaeus vannamei*: effects on growth and in vivo digestibility. *Aquaculture* 256:414–22.
Hernández C, Olvera-Novoa MA, Aguilar-Vejar K, González-Rodríguez B, De La Parra IA. 2008. Partial replacement of fish meal by porcine meat meal in practical diets for Pacific white shrimp (*Litopenaeus vannamei*). *Aquaculture* 277: 244–50.
Hu Y, Tan BP, Mai KS, Ai QH, Zheng SH, Cheng KM. 2009. Influence of dietary carbohydrate levels on growth and some physiological biochemical index in juvenile *Litopenaeus vannamei*. *Acta Hydrobiol Sin*. https://doi.org/10.3724/SP.J.0000.2009.20289.
Immanuel G, Menenthira V, Beena S, Palavesam A. 2003. Influence of dietary lipid on survival, growth and moulting strategies of *Penaeus indicus* (Milne Edwards) post larvae. *J Aquac Trop* 18:45–60.
Kanazawa A, Teshima S, Tokiwa S, Hirata M. 1979. Essential fatty acids in the diet of prawn:II. Effect of docosahexaenoic acid on growth. *Bull Jpn Soc Sci Fish* 45: 1141–53.
Katya K, Lee S, Yun H, Dagoberto S, Browdy CL, Vazquez-Anon M, Bai SC. 2016. Efficacy of inorganic and chelated trace minerals (Cu, Zn and Mn) premix sources in Pacific white shrimp, *Litopenaeus vannamei* (Boone) fed plant protein based diets. *Aquaculture* 459:117–23.
Köhrle J, Brigelius-Flohe R, Bock A, Gartner R, Meyer O, Flohe. 2005. Se in biology: facts and medical perspectives. *Biol Chem* 381:849–64.
Kurnia A, Muskita WH, Astuti O, Hakim A. 2016. Utilization of Telescopium mussel meal as an alternative protein source in the diet of black tiger shrimp, *Penaeus monodon*. *Int J Sci Res* 5(1):2006–11.
Lall SP. 2002. The minerals. In: Halver JE, Hardy RW (Eds.). *Fish Nutrition*, third ed. San Diego: Academic Press, San Diego. pp. 259–308.
Lee M-S, Shiau S-Y. 2003. Dietary copper requirement of juvenile grass shrimp, *Penaeus monodon*, and effects on non-specific immune responses. *Fish Shellfish Immunol* 13:259–70.
Li E, Yu N, Chen L, Zeng C, Liu L, Qin JG. 2010. Dietary vitamin B6 requirement of the Pacific white shrimp, *Litopenaeus vannamei*, at low salinity. *J World Aquac Soc* 41:756–63.
Lin YH, Shiau S-Y. 2005. Dietary selenium requirements of juvenile grouper, *Epinephelus malabaricus*. *Aquaculture* 250:356–63.
Liu XH, Ye JD, Kong JH, Wang K, Wang AL. 2013. Apparent digestibility of 12 protein-origin ingredients for Pacific white shrimp *Litopenaeus vannamei*. *N Am J Aquac* 75(1):90–8.
Macias-Sancho J, Poersch LH, Bauer W, Romano LA, Wasielesky W, Tesser MB. 2014. Fishmeal substitution with *Arthrospira* (*Spirulina platensis*) in a practical diet for *Litopenaeus vannamei*: effects of growth and immunological parameters. *Aquaculture* 426-427:120–5.
Nguyen BT, Koshio S, Sakiyama K, Harakawa S, Gao J, Mamauag RE, Ishikawa M, Yokoyama S. 2012. Effects of dietary vitamins C and E and their interactions on reproductive performance, larval quality and tissue vitamin contents in kuruma shrimp, *Marsupenaeus japonicus* Bate. *Aquaculture* 334-337:73–81.
Niu J, Lina HZ, Jiang SG, Chena X, Wua KC, Tian LX, Liu YJ. 2012. Effect of seven carbohydrate sources on juvenile *Penaeus monodon* growth performance, nutrient utilization efficiency and hepatopancreas enzyme activities of 6-phosphogluconate dehydrogenase, hexokinase and amylase. *J Anim Feed Sci Technol* 174:86–95.
Oujifard A, Seyfabadi J, Kenari AA, Rezaei M. 2012. Growth and apparent digestibility of nutrients, fatty acids and amino acids in Pacific white shrimp, *Litopenaeus vannamei*, fed diets with rice protein concentrate as total and partial replacement of fish meal. *Aquaculture* 342-343:56–61.
Ouraji H, Kenari AMA, Shabanpour B, Shabani A, Sodagar M, Jafarpour SA, Ebrahimi GH. 2011. Growth, survival, and fatty acid composition of Indian white shrimp *Fenneropenaeus indicus* (Milne Edwards) fed diets containing different levels of vitamin E and lipid. *Aquac Int* 19(5):903–16.
Rahman SHA, Razek FAA, Goda AMAS, Ghobashy AFA, Taha SM, Khafagy AR. 2010. Partial substitution of dietary fish meal with soybean meal for speckled shrimp, *Metapenaeus monoceros* (Fabricius, 1798) (Decapoda: *Penaeidae*) juvenile. *Aquac Res* 41:e299–306.
Rao MS, Anjaneyulu N. 2008. Effect of copper sulfate on molt and reproduction in shrimp *Litopenaeus vannamei*. *Int J Biol Chem* 2:35–41.
Richard L, Surget A, Rigolet V, Kaushik SJ, Geurden I. 2011. Availability of essential amino acids, nutrient utilization and growth in juvenile black tiger shrimp, *Penaeus monodon*, following fishmeal replacement by plant protein. *Aquaculture* 322:109–16.
Sales J, Janssens GPJ. 2003. Nutrient requirements of ornamental fish. *Aquat Living Resour* 16:533–40.
Sharawya Z, Ashraf MA-S, Goda M, Hassaan S. 2016. Partial or total replacement of fish meal by solid state fermented soybean meal with *Saccharomyces cerevisiae* in diets for Indian prawn shrimp, *Fenneropenaeus indicus*, Postlarvae. *Anim Feed Sci Technol* 212:90–9.
Smith DM, Tabrett S, Irvin S, Barclay M. 2006. Lupin—an alternative protein source for use in shrimp feeds. In: *Avances en Nutricion Acuicola Vlll, Vlll symposium Intemacional de Nutricion Acuicola, Monterrey, Nuevo Leon, Mexico*.
Suarez JA, Gaxiola G, Mendoza R, Cadavid S, Garcia G, Alanis G, Suarez A, Faillace J, Cuzon G. 2009. Substitution of fish meal with plant protein sources and energy budget for white shrimp *Litopenaeus vannamei* (Boone, 1931). *Aquaculture* 289: 118–23.
Sudaryono A, Tsvetnenko E, Evans LH. 1999. Evaluation of potential of lupin meal as an alternative to fish meal in juvenile *Penaeus monodon* diets. *Aquac Nutr* 5: 277–85.
Tacon AGJ, Metian M. 2008. Global overview on the use of industrially compounded aquafeeds: trends and future prospects. *Aquaculture* 285:146–58.
Tan B, Mai K, Zheng S, Zhou Q, Liu L, Yu Y. 2005. Replacement of fish meal by meat and bone meal in practical diets for the white shrimp *Litopenaeus vannamei* (Boone). *Aquac Res* 36(5):439–44.
Tan BP, Heng SX, Yu HR. 2003. Growth, feed efficiency of juvenile *L. vannamei* fed practical diets containing different levels of poultry by-product meal. NRA research Report No. 24. National Renderers Association, Inc., Hong Kong, China.
Terrazas-Fierro M, Civera-Cerecedo R, Ibarra-Martínez L, Goytortúa-Bores E, Herrera-Andrade M, Reyes-Becerra A. 2010. Apparent digestibility of dry matter, protein, and essential amino acid in marine feedstuffs for juvenile whiteleg shrimp *Litopenaeus vannamei*. *Aquaculture* 308:166–73.
Toledo TM, Silva BC, Vieira FN, Mouriño JLP, Seiffert WQ. 2016. Effects of different dietary lipid levels and fatty acids profile in the culture of white shrimp *Litopenaeus vannamei* (Boone) in biofloc technology: water quality, biofloc composition, growth and health. *Aquac Res* 47:1841–51.
Wang M, Changqu Z, Jin M, Huo Y, Li M, Xie F, Zhou Q. 2014a. Effects of dietary crude lipid level on growth performance, feed utilization and non-specific

immunity of Pacific white shrimp at two growth stages. *Chin J Anim Nutr* 26(9): 2687–97.
Wang XD, Li EC, Wang SF, Qin JG, Chen XF, Lai QM, Chen K, Xu C, Gan L, Yu N, Du ZY, Chen LQ. 2014b. Protein-sparing effect of carbohydrate in the diet of white shrimp *Litopenaeus vannamei* at low salinity. *Aquac Nutr* 21(6):904–12.
Watanabe T, Kiron V, Satoh S. 1997. Trace minerals in fish nutrition. *Aquaculture* 151: 185–207.
Wen M, Liu YJ, Tian LX, Wang S. 2015. Vitamin D_3 requirement in practical diet of white shrimp, *Litopenaeus vannamei*, at low salinity rearing conditions. *J World Aquac Soc* 46(5):531–8.
Xia MH, Huang XL, Wang HL, Jin M, Li M, Zhou QC. 2015. Dietary niacin levels in practical diets for *Litopenaeus vannamei* to support maximum growth. *Aquac Nutr* 21(6):853–60.
Xu WJ, Pan LQ. 2014. Evaluation of dietary protein level on selected parameters of immune and antioxidant systems, and growth performance of juvenile *Litopenaeus vannamei* reared in zero-water exchange biofloc-based culture tanks. *Aquaculture* 426-427:181–8.
Xue M, Yu Y. 2005. Digestion and growth response to dietary fish meal substitution with poultry by-product meal of shrimp (*P. monodon and L. vannamei*). NRA Research Report No. 49. National Renderers Association, Inc., Hong Kong, China.
Yang Q, Tan B, Dong X, Shuyan CS, Liu H. 2015. Effect of replacing fish meal with extruded soybean meal on growth, feed utilization and apparent nutrient digestibility of juvenile white shrimp (*Litopenaeus vannamei*). *J Ocean Univ China* 14(5):865–72.
Yang Q, Zhou X, Zhou Q, Tan B, Chi S, Dong X. 2009. Apparent digestibility of selected feed ingredients for white shrimp *Litopenaeus vannamei*, Boone. *Aquac. Res* 40:1–9.
Zhang SP, Li JF, Wu XC, Zhong WJ, Xian JA, Liao SA, Miao YT, Wang AL. 2013. Effects of different dietary lipid level on the growth, survival and immune-relating genes expression in Pacific white shrimp, *Litopenaeus vannamei*. *Fish Shellfish Immunol* 34:1131–8.
Zhao J, Wen X, Li S, Zhu D, Li Y. 2015. Effects of dietary lipid levels on growth, feed utilization, body composition and antioxidants of juvenile mud crab *Scylla paramamosain (Estampador)*. *Aquaculture* 435:200–6.
Zhou QC, Li CC, Liu CW, Chi SY, Yang Q-H. 2007. Effects of dietary lipid sources on growth and fatty acid composition of juvenile shrimp, *Litopenaeus vannamei*. *Aquac Nutr* 13:222–9.