Interactions between food, feeding and diets in crustaceans: A review

Mohd Amran Aaqillah-Amr 1, Ariffin Hidir 1, Mohamad Nor Azra 1, Mat Noordin Noordiyana 2 and Mhd Ikhwanuddin 1,3*

1 Higher Institution Centre of Excellence (HICoE), Institute of Tropical Aquaculture and Fisheries, Universiti Malaysia Terengganu, Malaysia (M.A.A:A. aaqillahamr_92@yahoo.com; AH: hidirariffin@gmail.com; M.N.A: azramn@umt.edu.my)
2 Faculty of Fisheries and Food Sciences, Universiti Malaysia Terengganu, Malaysia (M.N.N: diyananoor-din@umt.edu.my)
3 STU-UMT Joint Shellfish Research Laboratory, Shantou University, China
4 Correspondence: ikhwanuddin@umt.edu.my; Tel.: +609-6683501

Simple Summary: Unique food and feeding types which responds differently to various species among crustacean resulted in lack of published literature available focused on the formulating their diets. Thus, this review aimed to briefly explains the interaction between food, feeding and diets in crustacean. The pellet physical characteristics, their nutritive values and feeding behavior are important to improve the production of aquaculture species, especially the crustaceans. An updated knowledge on that subject are important to enhance the future commercialization of seafood production.

Abstract: There are several literatures that cover different views of crustacean food, feeding and behavior aspects, but little was known on its interaction between them and it’s also shown a different perspective. Thus, a better understanding of the interactions between food, feeding and diets in crustaceans is vital for developing better quality of seed or broodstock produced in hatchery and its adaptation to the aquaculture environment and system. The aim of the present review is to update the state of the art and to explicit the knowledge regarding food, feeding and diets in crustaceans and challenges and opportunities in the development of formulated diets.

Keywords: Food; feeding; diets; macro-micronutrients; feeding behavior; pellet-animal performances

1. Introduction

Interactions between food types, feeding behavior and formulated diets in the crustacean are important to improve the seed production and enhance fundamental knowledge of the cultured animals [1]. The development of pellet diets or aquafeed for aquaculture species has gained much interest nowadays as pellets offer many advantages compared to the natural feeds. In terms of nutrient content, artificial feed offers a nutritionally balanced diet with known nutrient content such as total lipid and protein that will promote growth and reproduction in the crustacean. By manipulating the level of protein and lipid important for growth and reproduction on crustacean’s group, the formulated feed could provide sufficient nutrition to broodstock. Initially, no commercial broodstock diet was available, for some crustacean species. Most formulated feeds are focused on the larval stages. There are not much published studies focused on formulating a feeding diet, particularly to some crustacean broodstock. This is probably because of the unique habitat characteristics which respond differently to different environment conditions [2]. Several species are restricted to certain environments and aquaculture systems that give effect to the type of feeding selection [3-6].
The growing demand for animal protein from existing competition between human need and aquaculture feeding resulted in the decreasing of fish landings since fish are the sole provider of n-3 PUFA in the diet. This adds to the existing gap between the demand and the supply for fish and fish products. Regarding this issue, many studies have covered some adjustments to the feeding formulation by not depending too much from fish source as the source of protein and lipid. As a replacement to fish oil and fishmeal, the use of terrestrial animal proteins such as meat, poultry by-product, bone meal, and blood meal have confirmed their efficiencies in providing the animals with good protein level [7].

Besides that, the use of protein sources from plant-based materials are getting more attention nowadays. Plant protein sources such as camelina meal, canola meal, and soybean meal can be used as a substitute to fish meal without imposing negative effects to the growth and feed intake [8]. However, the major setbacks lie with the use of protein source from the terrestrial animals and plant origin include the lack attractants and palatability factors [9]. Compared to aquatic animals such as fishmeal, shrimp meal, and squid meal, the lacking of attractants component may result in poor ingestion of feeds thus reducing the rate of feed intake which consequently will retard growth in the animals [10].

In general, the physical form of the pellets depends on the species being cultured. High moisture contents in the pellets are often associated with nutrient leaching since it dissociates easily upon entering the water. Apparently, low pellet stability and durability resulting from high moisture content may not be suitable for the crustacean, which some species are aggressive in handling foods [11]. In addition to that, the proper storage and handlings of the final products are difficult to manage especially for the wet pellet. Since the wet pellets have high moisture content, having a prompt spoilage such as mold problems due to long storage period is unavoidable.

In this review, we attempt to identify the interaction between food types, feeding behavior and formulated diets in crustacean, by summarizing all the available information on the topic using the title of the review as keywords in the Web of Science Core Collection database.

2. Food and Feeding

Table 1 summarized the crustacean’s feed types with pellet and animal performances. Most studies on feeding of crustacean was done at the juvenile stage, especially for shrimp, crayfish, and crabs, meanwhile lobster and prawn (and some on crab), most studies focused on the adult or broodstock stages (Table 2). There are several types of feed for broodstock used in the hatchery for commercial purposes: the wet feed, dry feed, semi-moist feed, and the moist feed. These feeds can be differentiated from each other in terms of moisture content where the moisture levels in each feed falls in the range of 45 – 70%, 7 – 13%, 25 – 45%, 15 – 25% for wet feeds, dry feeds, moist feeds, and semi-moist feeds respectively [12]. At the same time, water activity (aW) in the pellet defines better protection against bacterial growth where lower aW in the pellets are preferable. The aW differs from the moisture content where aW is defined as the ratio between the vapor pressure of the food in a completely undisturbed balance by the surrounding air media with the vapor pressure of distilled water under identical conditions. In most cases, pellets with aW of lower than 0.79 inhibits the growth of yeast whereas aW of lower than 0.65 successfully stops mold growth [13]. Wet, moist and semi-moist diets are more effective in terms of promoting good growth and feed efficiency owing to their soft texture and palatability. In this review, only two basic types will be considered for intensive farming; the dry feeds and the moist feeds (semi-moist will be included as it falls under the same category with moist feeds).
| Crustacean’s Group | Type of feed(s) | Pellet performance | Animal performance | Reference |
|-------------------|----------------|--------------------|--------------------|-----------|
| Prawn             | Floating soft pellet | Moist Floating soft pellet | Diets developed met the criteria of good water stability | Higher survival using formulated diet (fresh ingredient calf liver & artemia enrichment) | N/A | N/A | Marsden et al. [14] |
| Shrimp            | Commercial pellet Ground pellet (i) 300–1200 μm Dry pellet Dry pellet 2 mm | Dry pellet Carboxymethylcellulose (CMC) | N/A | Dietary inclusion of purple non-sulfur bacteria (PSNB) improved shrimp’s GP | N/A | N/A | Alloul et al. [15] |
|                   | Pressure (Extruded) pellet Extruded pellet | Dry pellet Wheat starch, whole wheat Dry meal, corn starch | N/A | All diets readily consumed with no indication of feed rejection | N/A | N/A | Samocha et al. [16] |
|                   | Extruded pellet | N/A | Dry pellet Wheat meal, corn starch | N/A | Fast growth (FG) shrimp genotype - higher growth rate than the high resistance (HR) shrimp genotype | N/A | N/A | Gonzalez-Galavis et al. [17] |
|                   | Extruded pellet | 0.5 mm diameter | Dry pellet Wheat starch, wheat gluten | Higher feeding rate | N/A | N/A | Velasco et al. [18] |
|                   | Extruded pellet | 2.4 diameter × 5.0 mm long pellet | Dry pellet Wheat whole hard red winter, wheat gluten meal | Lower retention; temperature & salinity affects dry matter retention rate | N/A | N/A | Obaldo et al. [19] |
|                   | Extruded pellet | Noodle-like | Dry pellet Wheat flour, wheat gluten | Visible behavioral differences among shrimp | Shrimp fed krill meal registered maximum weight gain, >86% | N/A | No difference in FCR or yield | Suresh et al. [20] |
| Pellet Type                      | Diameter/Strand | Matrix       | Binder          | Observations                                                                 | Survival in All Treatments | Among the Various Treatments |
|---------------------------------|-----------------|--------------|-----------------|------------------------------------------------------------------------------|----------------------------|-------------------------------|
| Extruded pellet                 | 4 - 5 mm strands| Wheat flour  | N/A             | 5-min leachate of intact pellet without any krill meal additive - strongest binder were apparent immediately after access to the feed Feed containing krill meal (as low as 1% up to 6%) enhanced ingestion of pellets | N/A                        | N/A                          | Derby et al. [21]             |
| Extruded pellet                 | 3 mm × 5 mm strand| Dry pellet  | Dry pellet      | Final mean weight significantly higher when formulated with 50% fish meal & 50% Spirulina | N/A                        | N/A                          | Gamboa-Delgado et al. [22]    |
| Extruded pellet                 | 1.4 mm orifices strands| Dry pellet  | Dry pellet      | Growth rates negatively correlated to dietary pea protein inclusion          | N/A                        | N/A                          | Martinez-Rocha et al. [23]    |
| Commercial extruded compound pellet | Strands with die plate - 1.4 mm in diameter | Dry pellet  | Dry pellet      | The diet incorporating ingredient-17 (soybean meal, dehulled, roasted, hexane-extracted and ground) showed largest weight gain | N/A                        | N/A                          | Fang et al. [24]              |
| Pressure (extruded) pellet      | 3 mm diameter pellet| Dry pellet  | Wheat starch    | Non-GM soy cultivars producing soybean meal show higher digestibility compared to white flakes or pressed soy cakes | N/A                        | N/A                          |                             |
| Sinking pellet                  | 3 mm pellets    | Steam pellet | Lignosol, agar  | Weight gain (WG) higher for *Palaemon elegans* than *Palaemonetes varians* fed diets with lignosol added by microbinding diet | Weight gain (WG) higher for *Palaemon elegans* compared to *Palaemonetes varians* | FCR was higher compared to *Palaemonetes varians* | Palma et al. [25]             |
| Feeding Method       | Feed Form          | Pellet Type     | Fortification/Components                                                                 | Palatability                              | Mean Weight Gains (N/A) | FCR were higher in shrimps fed difloxacin-medicated diets (N/A) | Shrimp fed diets formulated with FM significantly higher WG & specific growth rate (SGR) N/A | No significant difference between protein sourced from fish meal and soy meal (N/A) | Gil-Nunez et al. [28] | Park et al. [26] | Thang et al. [27] | Galkanda-Arachchige et al. [29] | Tazikeh et al. [30] | Moniruzzaman et al. [31] |
|---------------------|--------------------|-----------------|----------------------------------------------------------------------------------------|-------------------------------------------|-------------------------|------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|------------------------|---------------------|----------------------|--------------------------|------------------------|---------------------------|
| Extruded feed       | 3 mm diameter      | Dry pellet      | Aquabind                                                                                | Difloxacin was palatable at the 1× treatment level (100 mg/kg of feed) N/A | N/A                     | Mean weight gains by animals receiving difloxacin did not correlate with feed consumption (N/A) | The melanin coated with starch solution was strongly bound inside the feed N/A | N/A                                                                     |                                                                     |                    |                     |                      |                         |                       |
|                     | pellet             |                 |                                                                                        |                                           |                         |                                                                                 |                                                                              |                                                          |                                                                     |                       |                       |                       |                         |                       |
| Commercial pellet   | Bead form with a   | Dry pellet      | Cod oil, starch solution (3%), squid ink-sac liquid                                    | N/A                                      |                         |                                   | Melanin coated starch solution and melanin coated fish oil had protection rates of 57% and 67% at Day 7 respectively N/A |                                                                      |                                                                     |                       |                     |                      |                         |                       |
|                     | diameter of 2 mm   |                 |                                                                                        |                                           |                         |                                                                                 |                                                                              |                                                          |                                                                     |                       |                       |                       |                         |                       |
| Extruded pellet     | N/A                | Dry pellet      | Wheat flour, corn starch                                                                |                                           | N/A                     | Shrimp fed diets formulated with FM significantly higher PER N/A                 |                                                                      |                                                                    |                       |                     |                      |                         |                       |
| Extruded (pressed)  | 3 mm diameter      | Dry pellet      | Whole wheat, corn starch                                                                |                                           | N/A                     | Higher apparent digestibility of dry matter, energy, protein                    |                                                                      |                                                                    |                       |                     |                      |                         |                       |
|                     | pellet             |                 |                                                                                        |                                           |                         |                                                                                 |                                                                              |                                                          |                                                                     |                       |                       |                       |                         |                       |
| Steam pellet        | 1 mm diameter      | Dry pellet      | CMC                                                                                     | Feed consumption was higher in the 50% meat & bone meal with garlic supplementation | N/A                     | SGR were higher in shrimp fed with supplementation of meat & bone meal with garlic compared to meat & bone meal alone N/A | High PER was recorded in feeds supplemented with meat & bone meal with garlic N/A | High PER was recorded in feeds supplemented with 50% meat & bone meal with garlic N/A |                       |                     |                      |                         |                       |
| Steam pellet        | N/A                | Dry pellet      | CMC                                                                                     | Apparent digestibility of feeds & ingredients higher in fish fed the bioprocessed protein concentrates significantly higher growth performance at 30% fish meal replacement N/A | N/A                     | Shrimp fed the bioprocessed protein concentrates showed significantly higher feed efficiency (FE) N/A |                                                                      |                                                                     |                       |                     |                      |                         |                       |
| Order | Species | Form of Feed | Composition | Retained Dry Matter | Binding | Results | References |
|-------|---------|--------------|-------------|---------------------|--------|---------|------------|
| Crayfish | Steam sinking pellet | 5 mm diameter conglomerated structured | Carrageenan, Cardoxymethyl-cellulose (CMC), agar & gelatine | 5% binder retained more dry matter compared to 3% binder | N/A | N/A | Ruscoe et al. [32] |
| Extruded pellet | 1 cm diameter spaghetti like structure | Dry pellet | Carboxymethylcellulose (CMC) | N/A | Diet 4 containing menhaden fish meal, soybean meal, choline chloride, cod liver oil & corn oil may satisfy the lecithin & cholesterol requirements | N/A | Thompson et al. [33] |
| Extruded Pellet | 1 cm × 0.1 cm diameter with Spaghetti into cylindrical from N/A | Dry pellet | Pectin, alginate & chitosan | Pectin diet showed good water stability | N/A | Pectin diet showed highest wet gain | Volpe et al. [34] |
| Extruded pellet (Stable and unstable pellet) | Dry pellet | Maize, oat flour | Stable pellets promote lower leaching rate & faster growth than unstable diets | Marron handled and ingested the intact stable pellets, and ingested unstable pellets for as long as they stayed in form of a pellet | N/A | Crayfish fed stable diets have higher SGR than the unstable diets and control feed | Jussila & Evans [35] |
| Crab | Steam pellet | 1 cm diameter; compounded feed (ball form and pellet form) | Semi-moist & dry pellets | Semi-moist ball feed showed higher dry matter loss (30.4%) during feeding | N/A | Crabs showed excellent acceptance of the feeds | Ahamad-Ali et al. [36] |
| Pellet Type       | Diameter/Length | Material                  | Protein (g) | Fat (g) | Ash (g) |
|------------------|----------------|---------------------------|-------------|---------|---------|
| Steam pellet     | 1.2 mm diameter; 4.0 mm length | Guar gum                  | 22.6         | 13.1    | 4.7     |
| Extruded pellet  | 4-6 mm length  | Dextrin                   | N/A          | N/A     | N/A     |
| Steam pellet     | 1×1×0.3 cm jelly cubes | Agar-agar                | 11.3         | 6.8     | 3.9     |
| Steam pellet     | 1×1×0.3 cm jelly cubes | Agar-agar                | 12.5         | 7.2     | 4.1     |
whereas 1.12% cholesterol had an adverse effect on mud crab growth. The weight gain of crabs fed diets containing 22:6n-3 or 20:4n-6 was higher than those fed the diets without supplemented PUFA.

| Diet Type | Pellet Type | Jelly | Agar-agar | Binder | Regression Analysis | Lobster Growth | Lobsters Growth | SGR in Lobster Fed with Mussel | Growth | Feed Conversion | Authors |
|-----------|-------------|-------|-----------|--------|---------------------|----------------|----------------|-----------------------------|--------|---------------|---------|
| Lobster   | Steam       | 1×1×0.3 cm jelly cubes | Moist | Agar-agar | N/A | N/A | N/A | N/A | Sheen & Wu [44] |
|           | Steam       | 5 - 9 mm cylindrical rod pellet | Moist | Aquabind | Regression analysis showed no significant difference in water stability between pellets | Lobster fed with pellets from krill meal had greater feed intake than lobster fed with pellets from fish meal | Lobsters fed with pellets from fish meal and krill meal; had greater energy than pellets from fresh items homogenized | SGR in lobster fed with mussel was higher than other formulated feeds | N/A | N/A | Marchese et al. [45] |
|           | Steam       | 10 - 20 mm length passed through 4 mm diameter die | Dry | Aquabind | N/A | N/A | N/A | Equivalent growth for all trial lobster | Higher feed supplied conversion ratios of pellet-fed treatments | N/A | N/A | Bryars & Geddes [46] |
|           | Steam       | 4 mm diameter | Dry | Tapioca powder, agar-agar, ‘stick on’ a phytochemical, gum Arabic, guar gum, wheat flour, gelatin, and Basal diets with binders | Basal diets performed the highest stability compared to other binder combination | Lobster showed good acceptance of basal diets and palatability as recorded through behaviour | N/A | N/A | N/A | Saleela et al. [47] |
### Table 2: Crustacean’s feeding behaviour and life stages

| Crustacean’s group | Life history stage | Feeding habit | Feeding behavior | Feeding time | Reference |
|--------------------|--------------------|---------------|------------------|--------------|-----------|
| **Shrimp**         | Juvenile           | Ingestion of food is controlled by mouthpart and esophageal chemoreceptors | Up to satiation | Animals were fed once daily in the late afternoon | Derby et al. [21] |
|                    | Juvenile           | Shrimps are slow and continuous eaters | 10% body weight | Fed once a day in the morning (10:00 h) | Palma et al. [25] |
|                    | Juvenile           | N/A | 5% of cumulative animal body weight per tank | Once per day in the morning | Park et al. [26] |
|                    | Juvenile           | N/A | Fed in excess | Animals were fed four times per day | Galkanda-Arachchige et al. [29] |
|                    | Juvenile           | N/A | 4% of wet body weight in the first 4 weeks and 3% in the second 4 weeks, with apparent satiation | Shrimps were fed four times a day (08:00, 12:00, 16:00, 20:00). | Gamboa-Delgado et al. [22]; Moniruzzaman et al. [31] |
|                    | Juvenile           | N/A | Fed initiating with 10% of total shrimp biomass, adjusting it weekly | Fed at satiation three times a day (08:00, 13:00, and 18:00 h) | Gil-Núñez et al. [28] |

*N/A: Not available*
| Animal | Stage | Feeding Behavior | Diet Specification | Feeding Schedule | References |
|--------|-------|-----------------|--------------------|-----------------|------------|
| Crayfish | Juvenile | Slow feeding response | N/A | Fed three times daily (07:30, 12:30, and 16:00 h) | Thompson et al. [33] |
|        | Juvenile | Slow feeder / Manipulate food using mouth appendages before ingestion | 5% body weight | Animals were fed every day between 8:00 and 9:00 am | Volpe et al. [34] |
|        | Juvenile | Slow intake, prolonged handling, long intervals between food intakes | 6.5% body weight | Feed daily | Jussila & Evans [35] |
| Crab   | Immature / Mature | Omnivorous scavengers, opportunistic feeder; crabs approach and grab feeds with chelae | 10% body weight | Fed twice; 11 am & 4 pm | Ahamad-Ali et al. [36] |
|        | Juvenile | Show preference for detritus | Fed to satiation (about 2 - 3.5% body weight) | Fed twice daily at satiation level | Catacutan [37] |
|        | Juvenile | N/A | Fed with excess diets | Fed twice a day at 8:00 hours and 18:00 hours | Zhao et al. [39] |
|        | Juvenile | N/A | 6% body weight | Fed twice daily (at 07:00 hrs and 17:00 hrs) | Unnikrishnan et al. [40]; Unnikrishnan & Paulraj [41] |
|        | Broodstock | N/A | 1.0% dry matter basis of the crab biomass | Twice daily; half in the morning, half in the afternoon | Alava et al. [50] |
| Lobster | Juvenile | Cannibalistic; rely on chemoreception; slow feeder Opportunistic predator | 50% body weight | Fed twice daily (morning and afternoon) | Marchese et al. [45] |
|        | Subadult | Bottom dwelling animal; slow intermittent feeder | N/A | Fed twice daily | Perera et al. [48] |
|        | Adult | N/A | Lobster fed at rate 2% of their BW per day, given two feeds per week of 7% BW | Nocturnal; fed single dose daily (18:00 hours) | Saleela et al. [47] |
| Prawn  | Broodstock | N/A | Fed to slight excess | 10.00 and 17.00 daily | Marsden et al. [14] |

*N/A: Not available*
2.1 Dry pellet

The use of dry pellets can be in variety form; the dry-sinking pellet, extruded sinking pellet, and extruded floating pellet. The suitable feed ingredients selection with proper manufacturing procedures such as the extrusion process ensure good water stability which is the main criteria in producing good feeds. The extrusion method is different from the steam pellet in a way that the extruder does not use any pellet binder to add adhesion to the particles. Extruded pellets are more brittle where they only expand through gelatinization of starch upon cook [51]. During the gelatinization process, the starch becomes activated and absorbs large volumes of water. Tuber starches such as potato and tapioca are popularly used as binding agents since they are high in amylase enzyme [52].

Overall, the production of dry-sinking pellets is more practical for bottom feeders such as crustaceans, particularly prawns, lobsters, and crabs. Among the necessary steps in the formulation of water-stable dry pellets include the use of good binding agents plus finely ground ingredients to ensure maximum adhesion of the binder molecules. Whereas, the application of extruded floating pellets is more suitable for fish species which predominantly feed in the water column such as tilapia, trout, grouper, sea bass, and carp. The use of floating pellets allows observation on feeding activity other than the fish well-being [53].

2.2 Moist pellet

Moist pellets or wet pellets consist of a combination of high moisture ingredients and dry pulverized ingredients. The use of moist feed is widely accepted among the aquaculture’s practitioners for maturation of broodstocks [36]. Regardless of their acceptance to use in the hatcheries, no commercialization of moist feeds has been produced presently. Due to their high moisture content, the moist pellets have low water stability and are prone to mold problems. Meanwhile, the innovation of semi-moist pellets has been successfully developed at laboratory scale. Compared to moist pellets, the moisture content of semi-moist pellets is under the permissible level with the addition of chemical agents to avoid yeast and mold growth.

2.2.1 Palatability and attractability

Optimization of feed intake is determined by a good physical attribution of the pellet which includes the palatability and acceptability of the animals towards the feed, considering the species behavior and their physiological requirements as well [32]. Priority is given in ensuring that the nutrient is reached to the animal with minimum leaching. Absence of attractants and palatability features in the pellets resulted in the declining feed consumption hence resulted in the poor growth in the crabs. The palatability and the attractability of the feeds are thus necessary which will lead to good digestion and utilization of the prepared nutrients. Palatability is defined as the acceptance of the animals towards the food, resulting in the increasing of the body weight whereas attractability involves the animal’s orientation towards the presence of, one of the two feeds that have been offered [20].

Both palatability and attractability have become a primary factor in the development of cost-effective feed since animals have great sense of smell, taste and sight to search for food. Both physical features ensure higher feeding rates in the animals. Diets of low-palatability and attractability will result in crabs not being able to reach optimum nutritional requirements. Good palatability is determined through the feed intake [54] and low food conversion ratio (FCR) as indicator to the efficiency of the feed or feeding strategy [55]. A good attribution in the pellet such as strong smell and good binding factor will help the crabs find the pellet as well as reducing the risk of nutrient loss due to leaching problems. Insufficient levels of attractants factors can result in low feed intake which eventually resulted in poor growth of the organisms.
2.2.2 Type of binder

Aquatic feed formulation involves the use of good quality binding agents as the primary ingredient that help in stabilizing feed during exposure to water and at the same time enhance feed floatation time [56]. Vast binders have been used while formulating high durability pellets to increase the water stability and minimize nutrient leach by adding cohesion to the particles and reducing the void spaces. This includes agar, starch, gelatine, carrageenan, and carboxymethylcellulose (CMC). Good binder selection with correct inclusion level in the diet formulation will determine the overall pellet performance against nutrient leaching, water stability and turbidity of the ponds. Practically, binders that can be digested and assimilated are chosen. Polysaccharides such as starch plays an important role in the aquafeed development in providing the animals with necessary carbohydrates as well as a binder responsible in the adhesion of the feed components. Extruded pellets depend on the gelatinization in the starch since no binders are used in the formulation. Starch such as maize, millet, guinea corn, wheat, and cassava improve the pellet durability, contain high protein level and make a good binder in the extruded feed pellets [8]. These types of binder are capable of generating air traps in the formulated feeds thus improving the physical integrity of the feeds in the water.

On the other hand, the use of unbranched polysaccharide from the seaweeds such as the agar, sodium alginate, and carrageenan have been widely applied in the field of aquaculture nutrition, mainly as binder. Ruscoe et al. [32] compared the use of carrageenan, CMC, agar, and gelatin as the binders at different concentration in freshwater crayfish and concluded that carrageenan and CMC at 5% concentration were significantly better than both agar and gelatin. Meanwhile, research carried out by Paolucci et al. [57] regarded that agar performed better compared to both sodium alginate and carrageenan during feed manufacturing. Agar is usually activated when heated up to 80 – 85°C and the binding of feed components generally begin once the solution cools down to gelling temperature of range 32 – 43°C [57].

2.2.3 Water stability and durability

Compared to fish pellets, the pellet disintegration and nutrient leaching in crustacean pellets require more attention because of their nature as a benthic organism and a slow feeder [19]. Physical features such as the pellet stability and durability especially are more critical than other species where larger pellet sizes are used [32] with longer soaking hour and the least possible leaching of nutrients [58]. It is suggested that the crustacean pellets must maintain a minimum of 90% dry matter retention even after 1 hour exposure in water, thus the use of dry pellets is not suitable as it does not solve the nutrient leaching problems [59]. Crustaceans especially crabs and crayfish are very robust in terms of handling foods using their cheliped and the mouth appendages to grasp and break up the food to smaller bites prior to ingestion [32, 34] in which sinking and water stable pellets are necessary.

The pellet water stability is defined as the ability of the pellet to retain its integrity and nutrients while in water until consumed by the animal [19]. Meanwhile, durability is defined as the ability of the pellet to maintain its shape while handling, transportation, and inflatble transmission, without breaking it to smaller particles [51]. In aquatic pellets, the stability of pellets while in water is determined by the type of binding agent that holds the pellet together. Good water stability in pellets defines its effectiveness in optimizing feed intake in the crabs from harsh handlings and vigorous mastication so the nutrients required for growth will be fulfilled. Internal factor such as slow feeding rate and external factors such as high water currents and strong aeration in the tank will accelerate pellet disintegration which can result in the nutrient leach [32, 51] and consequently increase the water clarity and turbidity from the suspended materials. The use of binders helps in holding the feed components together, minimizing the void spaces, maintaining pellet integrity thus producing a more compact and durable pellet [32].
2.2.4 Buoyancy

For fish, floating feed is fundamental for optimum feed intake since fish are fast swimmers and naturally eat at the water column [60]. The use of different ingredients combinations particularly the binder agent exhibits greater pellet characteristics such as pellet buoyancy, good water stability, digestibility, minimum wastage of raw materials, as well as low water pollution [61]. Fish feeds specifically require good binding agents that will help in stabilizing the feed and prolong the feed floatation period when in water while maintaining its nutritional value. Sinking of the uneaten feeds to the bottoms of the pond as a result of short floatation time will eventually deteriorate the water quality and might end up as fertilizer which triggers the algal blooms from the high nutrient inputs [62]. Plus, additional cost may be incurred while maintaining good water quality due to low feed performance [63]. The good binding agents contribute to minimum wastage and provide the fish with optimum nutrient utilization [56]. The use of floating feeds are advantageous as they help the farmer to closely observe the feeding activity of the fish and the uneaten feed can be discarded immediately thus preventing the low water quality problems since they afloat at the water column [64].

Unlike fish, for a bottom feeder and slow eater particularly, the long-term sinking pellets are preferable, characterized by a less expanded structure and high densities. Compared to floatation fish feeds, the sinking pellets offer longer time taken to float to suit the slow, bottom feeder such as the crayfish [32], shrimp [65, 66] and mud crabs [36, 67]. For these reasons, the moist or dry sinking pellets are more appropriate since they are high in density compared to the floating pellets. Experiments on soft shell portunid crabs observed that crabs having a hard time grasping the floating feed with their claws signifying that the sinking pellet would be more appropriate [67].

3. Diets

Table 3 shows the macro and micronutrients at different crustacean life stages. The main group of nutrients in crustacean related diet studies are protein, carbohydrates and lipids considered as macronutrients, meanwhile vitamin, minerals and feed additives are the micronutrients group (Table 3). Nutrition plays an important role in the development of ovaries [68]. Although some crustacean species can survive a period of starvation due to insufficient food supply; either from the hatchery of wild, more lipid reserves are used to sustain energy metabolic functions thus retards growth and reproduction activities in the crustacean [69]. Selectivity of feed in the aquaculture will determine the time taken for the crustacean to reach sexual maturation. Lipid and protein are described to be the most important component of the nutrient classes that act as main source of nutrient for embryonic development [70].

3.1 Protein requirement for crustacean broodstock

Protein is one of macronutrients in crustacean feed ingredients that takes part in promoting growth, fattening, and reproduction of aquatic animals. Optimum protein levels are especially important in juvenile crabs since they actively grow through molting activities. Inadequate amount of protein supplies hinders growth [71], sometimes causes mortalities especially in the juvenile crabs from the prolonged intermolt period [41]. Yet, dietary protein surplus results in water deterioration from degradation of protein leftovers to form ammonia or urea [72].
| Crustacean’s group | Life stage | Protein | Carbohydrates | Lipid derivatives | Micronutrients | Feed additives | Reference |
|-------------------|------------|---------|---------------|-------------------|----------------|----------------|-----------|
| **Prawn**         | Adult      | 54.6%   | N/A           | 10.7%             | 5.0%           | Lecithin       | Marsden et al. [14] |
|                   |            |         |               | 1.1%              | 3.0%           |                |           |
|                   |            |         |               | ARA = 2.4%        |                |                |           |
|                   |            |         |               | EPA = 11.2%       |                |                |           |
|                   |            |         |               | DHA = 32.9%       |                |                |           |
|                   |            |         |               | β-carotene 0.004; Astaxanthin 0.004 | |                |           |
| **Shrimp**        | Postlarvae | Isonitrogenous | N/A           | 77.1 - 85.9% | 2.5%     | Soy lecithin, anti-fungal, antioxidant (ethoxyquin), Vitamin E | Martinez-Rocha et al. [23] |
|                   |            | feed 21% dry weight |            | 3%            | 2.0%     | Lecithin, alpha cellulose, alginate, sodium hexameta-phosphate | Velasco et al. [18] |
|                   |            |         |               | N/A            | N/A     | Calcium phosphate dibasic, lecithin, StayC  | Samocha et al. [16] |
|                   |            |         |               | 0.5%           | N/A     | Soybean lecithin, algicin acid | Gonzalez-Galaviz et al. [17] |
|                   | Postlarvae | 30%     | 42.1%         | 6%              | 1.0%     |                |           |
|                   |            |         |               | 0.5%           | 4.7%     |                |           |
|                   |                |         | N/A           | DHA: 0.5%       |                |                |           |
|                   |                |         | N/A           | ARA: 0.13%      |                |                |           |
|                   |            |         |               | N/A            | N/A     |                |           |
|                   |            |         |               | 8.53%          | 8.53%    |                |           |
|                   |            |         |               |                |         |                |           |
|                   |                |         | N/A           | 5.84%          | 2.0%     | Lecithin, alginate | Suresh et al. [20] |
|                   |            |         |               |                | 0.2%     |                |           |
|                   |            |         | N/A           | 8%             | 1.8%     | Choline chloride, Stay-C 35% active | Galkanda-Arachchige et al. [29] |
|                   |            |         |               |                | 0.5%     |                |           |
|                   |            |         | N/A           | 0.1%           | 1.8%     | Choline chloride, Stay-C250 mg/kg, CaP-diebasic, lecithin, chromium oxide | Fang et al. [24] |
|                   |            |         |               |                | 0.5%     |                |           |
|                   |                |         | N/A           | 8%             | 1.8%     | Calcium phosphate, soya lecithin | Palma et al. [25] |
|                   |            |         |               |                | 0.5%     |                |           |
|                   |            |         | N/A           | 9.1%           | 2.0%     | Krill meal, monocalcium phosphate, lecithin | Derby et al. [21] |
|                   |            |         |               |                | 0.5%     |                |           |
|                   |            |         | N/A           | 9.45%          | 2.0%     |                |           |
|                   |            |         |               |                | 0.28%    |                |           |
|                   |            |         | N/A           | 0.16%          | 0.28%    |                |           |
| Juvenile | 34.8% protein in feed with soy meal and 29.3% protein in feeds with fish meal | 38.76% in feed with soy meal and 22.45% in feed with fish meal | 6.65% in feed with soy meal and 5.84% in feeds with fish meal | N/A | N/A | N/A | 0.93% in feed with soy meal and 0.85% in feed with fish meal | 0.93% in feed with soy meal and 0.85% in feed with fish meal | Soy lecithin, alginic acid, cellulose, antioxidant | Gil-Núñez et al. [28] |
|-----------|------------------------------------------------------------------|-----------------------------------------------------------------|----------------------------------------------------------------|-----|-----|-----|------------------------------------------------|------------------------------------------------|------------------------------------------------|----------------------------------------------------------------|
| Juvenile | 35.8% to 36.6% dry weight                                       | 34.7% to 38.9%                                                  | 7.9% to 8.1%                                                    | 0.2%| N/A | N/A | 0.5%                                             | 0.5%                                                   | Lecithin-soy, methionine, lysine, titanium dioxide | Weiss et al. [73] |
| Juvenile | Isonitrogenous feed 40% dry weight                              | N/A                                                             | Isolipidic feed 9.00% dry weight                                | 0.02%| N/A | N/A | 1.2%                                             | 1.0%                                                   | Lecithin powder 97%, amygluten                                          | Moniruzzaman et al. [31] |
| Juvenile | Isonitrogenous feed 35% dry weight                              | 31.93-32.78%                                                   | 8.18 - 8.63% lipid                                             | N/A | ARA:1.68%; EPA: 2.87%; DHA: 4.66%             | N/A | 15%                                             | 25%                                                   | Dicalcium phosphate, antifungal, antioxidant, lysine, methionine, garlic powder | Tazikeh et al. [30] |
| Juvenile | Isonitrogenous feed 36% crude protein                           | N/A                                                             | 7.9 - 9.00% lipid                                              | 0.11%| N/A | N/A | 0.25%                                             | 0.25%                                                  | Antioxidant, antifungal agent, Vitamin C, choline chloride, Monocalcium phosphate, cellulose | Gamboa-Delgado et al. [22] |
| Juvenile | 37%                                                             | 38.32 to 38.88%                                                | 10%                                                            | 0.5%| N/A | N/A | 1.46% (5% from 29.23% carotenoid extracted)    | 1.0%                                                   | Sodium (1.4% to 1.5%), Calcium (3.3%) & Iron (0.7% to 1.3%)              | N/A                                                   | Volpe et al. [34] |

| Crayfish | Isonitrogenous with 39.02% to 39.74% dry weight                 | 41.38% to 44.00% dry weight                                    | Isolipidic 7.03% to 7.53% dry weight                           | 12.6% to 12.9% dry weight | Saturated with 2.52% to 2.72% dry weight and unsaturated with 4.51% to 4.81% dry weight | ARA: 1.09%; EPA: 3.38%; DHA: 7.94% | N/A | 2.0%                                             | 0.5%                                                   | Lecithin, dicalcium phosphate, Vitamin C, choline chloride             | Thompson et al. [33] |
| Category | Stage | Composition | Diet | DHA/EPA Ratio | Other Nutrients | Source |
|----------|-------|-------------|------|---------------|----------------|--------|
| Crab     | Juvenile | 44.85% to 46.73% dry matter | N/A | 7% and 12% lipid | N/A | 1.00% | 1.50% | Monocalcium phosphate, choline chloride, cellulose | Wang et al. [74] |
| Juvenile | Isonitrogenous with 43.64 to 46.08% dry weight | 17.2 kJ g⁻¹ | Dietary lipid level of 8.52% – 11.63% (optimum 9.5%) | 0.8% | ARA: 0.5%; EPA: 14.1%; DHA: 11.7% | N/A | 3.00% | 2.00% | Lecithin, sodium alga acid, squid paste, cellulose | Zhao et al. [38] |
| Juvenile | Isonitrogenous feed with 45% crude protein | N/A | Isolipidic diets containing 9.5% oil (fish oil, lard, safflower oil, perilla seed oil or mixture oil | 0.8% | ARA: 0.5%; EPA: 6.9%; DHA: 6.1% | N/A | 3.00% | 2.00% | Lecithin, sodium alga acid, squid paste, cellulose | Zhao et al. [39] |
| Broodstock | Isonitrogenous with 41.57% dry weight | 24.94% | Isolipidic feed 81% dry weight | 0.5% | N/A | N/A | 1.00% | 2.00% | Lecithin | Ahamad-Ali et al. [36] |
| Broodstock | 42% protein dry weight | 17.2 MJ kg⁻¹ | 10% lipid dry weight | 0.167% dry weight | ARA: 0.15%; EPA: 0.44%; DHA: 1.11% dry weight | N/A | 3.0% | 3.0% | Soy lecithin, dicalcium phosphate, phosphitan C, alphatoxopheryl acetate | Alava et al. [50] |
| Juvenile | 46.9% to 47.03% dry weight | N/A | Isolipidic feed 10% dry weight | 0.50% | N/A | 0.009% β-carotene | 1.50% | 5.00% | Cellulose, dextrin, lecithin | Unnikrishnan & Paulraj [41] |
| Juvenile | Isonitrogenous with 45% dry weight | N/A | Isolipidic with 10.8% dry weight | 0.50% | 0.13% ARA; 0.64-0.66% EPA & 0.37-0.38% DHA | 0.009% β-carotene | 1.50% | 5.00% | Cellulose, dextrin, lecithin | Unnikrishnan et al. [40] |
| Juvenile | 32 to 40% dry weight | 17.2 MJ kg⁻¹ | 6% or 12% dry weight | 0.1% | N/A | N/A | 1.50% | 0.50% | Seaweed, soy lecithin, dicalphos | Catacutan [37] |
|                | Protein Content  | Lipid Content          | Carotenoids | Fatty Acids | Other Ingredients                                                                 | Source                          |
|----------------|------------------|------------------------|-------------|-------------|------------------------------------------------------------------------------------|---------------------------------|
| **Juvenile**   |                  |                        |             |             |                                                                                   |                                 |
| Isonitrogenous | 48.5%            | 5.3 to 13.8% lipid dry weight | 1.0%        | 0.36-0.4% ARA; 6.54-7.03% EPA; 2.29-2.81% | 0.01% Astaxanthin               | 4.00% Taurine, choline chloride, vitamin A, Vitamin D₃, Vitamin E | Sheen & Wu [42]                 |
|                |                  |                        |             |             |                                                                                   |                                 |
| 46.6% protein  | 46.6% protein dry weight | 8.6% lipid dry weight | 0.51%        | N/A         | 0.01% Astaxanthin                                                             | 4.00% Taurine, choline chloride, vitamin A, Vitamin D₃, Vitamin E | Sheen [43]                      |
| dry weight     |                  |                        |             |             |                                                                                   |                                 |
| 44.0 - 45.7%   | 44.0 - 45.7% dry weight | 1.1% to 1.08% lipid dry weight | 0.5% dry weight | 0.2% ALA, 0.2% ARA, 0.2% DHA dry weight | 0.01% Astaxanthin               | 4.00% Taurine, choline chloride, vitamin A, Vitamin D₃, Vitamin E | Sheen & Wu [44]                 |
| dry weight     |                  |                        |             |             |                                                                                   |                                 |
| **Lobster**    |                  |                        |             |             |                                                                                   |                                 |
| Juvenile       | Isonitrogenous   | 10.04%                 | 2%          | N/A         | 1% Carophyll pin (8% astaxanthin)                                                 | 1.1% Lecithin, Stay-C            | Marchese et al. [45]            |
| 53% dry weight |                  |                        |             |             |                                                                                   |                                 |
|                | 25% and 35%      | 23.75 - 24.73%         | 6.2 - 7%    | N/A         | N/A                                                                                 | 5% Vitamin C, Calcium carbonate, dicalcium phosphate | Perera et al. [48]              |
|                | protein          |                        |             |             |                                                                                   |                                 |
|                |                  |                        |             |             |                                                                                   |                                 |
| Subadult       | 54.5%            | 17.6%                  | N/A         | N/A         | N/A                                                                                 | 1% Casein, cod liver oil, sodium chloride di-sodium hydrogen orthophosphate and supradin powder | Bryars & Geddes [46]            |
|                |                  |                        |             |             |                                                                                   |                                 |
| Adult          | N/A              | N/A                    | N/A         | N/A         | 0.15% and 0.25% Carophyll Pink                                                      | 0.2% Vitamin C, lecithin, Banox E |                                 |
|                |                  |                        |             |             |                                                                                   |                                 |

*N/A: Not available*
Hence, information on the dietary protein requirement is of vital importance to ensure good growth and maturation. Many investigations have been carried out to determine the protein requirement in different crustaceans such as prawns, shrimps, swimming crabs, and mud crabs. The results showed that the protein requirements are species specific, ranging from 22% – 60% [37, 41, 72] where the dietary protein intake in juvenile or early life stage of animals are usually higher compared to the matured animals for most crustacean species.

3.2 Lipid requirement for crustacean broodstock

Lipid encompasses various classes of organic molecules such as triacylglycerols, phospholipids, sterols, waxes, carotenoids, and fatty acids [10]. Lipids, along with proteins and carbohydrates share the same importance in terms of providing the body with energy. Lipid differs from protein and carbohydrates in a way that it provides energy twice than both proteins and carbohydrates, serve as the structural components of cell membranes, and as important signaling molecules [75]. Neutral lipids, particularly triacylglycerols or also known as triglycerides are the principal form of energy source found in the adult, egg, and larvae of most crustaceans [50]. The phospholipids primarily functions in the building of the cell membrane [76], whereas, the cholesterol is the best known sterols that serves as a precursor of physiological components including sex hormones, particularly ecdysone that regulates molting activities in the crustaceans [43, 77]. Feedings containing dietary cholesterols are essential to ensure good growth and survival in the crabs. Fatty acids govern a wide range of physiological processes including the reproductive performance and egg quality in crustaceans [70].

Studies demonstrated that the lipid levels in most crustaceans increased with size where the adults have higher lipids than the juveniles. Some reserved lipids are catabolized as energy while others are stored in the gonad for structural purposes, such as maturation and eicosanoid synthesis [78]. The information on the lipid requirement is very important for the development of formulated feed to ensure the nutrients suffice for good growth and maturation [10]. Previous studies showed that the determination of lipid requirements are generally species specific and are basically different at different developmental stages. Nevertheless, collective studies on crustaceans concluded that optimum growth can be achieved with a total lipid level from 2 – 10% [39] or from 2 – 12% of diet dry weight [37].

The fatty acids can be further divided into several classes; the saturated fatty acids (SAFA), monounsaturated fatty acid (MUFA), and polyunsaturated fatty acids (PUFA). Fatty acids that have no double bond are grouped as SAFA, while MUFA are categorized as fatty acids that have a single double bond in their carbon chain. Unlike SAFA and MUFA, polyunsaturated fatty acids (PUFA) contain more than one double bond in its carbon backbone. They act as precursors for animal hormones and play an important role in regulating cell membrane. PUFA are commonly generated from the plant synthesis as the primary producers of carbon in marine ecosystems, synthesizing various important biological molecules such as carbohydrates, proteins and lipids [79]. Most animals do not have the ability to synthesize PUFA de novo except for their capacity to convert one form of PUFA to another form through elongation and desaturation. Such fatty acids are termed as the essential fatty acids (EFA) as they must be taken in through the diet. This includes linoleic and linolenic acid since not all animals have the ability to produce them [80].

Meanwhile, the highly unsaturated fatty acids (HUFA) are the subset of PUFA, having 20 or more carbon atoms with 3 or more double bonds. They are responsible for survival, maintaining high growth rates and reproductive rates as well as high food conversion in both marine and freshwater organisms [80]. Arachidonic acid (ARA, C20:4n6), eicosapentaenoic acid (EPA, C20:5n3), docosahexaenoic acid (DHA, C22:6n3) are among the derived omega-6 and omega-3 long chain of HUFA (n-3 and n-6 LC PUFA; C ≥ 20). The consumption of diet containing EPA and DHA help to optimize animal growth [80] while ARA functions as the precursor for eicosanoids that regulates reproductive success.
and sexual behaviour of females [81]. In general, EPA and DHA can be obtained from the consumption of plant materials or through series of elongation and desaturation of α-linolenic acid (ALA, C18:3n3). Whereas, elongation and desaturation of linoleic acid (LA, C18:2n6) will produce ARA. During the desaturation and elongation process, both n-3 and n-6 PUFA from ALA and LA will compete for the same desaturation enzyme to produce LC-PUFA [82, 83].

5. Conclusions

The importance of pellet physical characteristics in aquaculture nutrition cannot be overemphasized. The advantages of good quality pellets not only depend on the binding agent alone, but the attractants that enhance palatability as well as the inclusion of the correct proportion of nutrients to boost animal performance. The updated knowledge on the possible interactions between food, feeding and diets in crustaceans needs to be improved to increase the quality of seed or broodstock produced in captivity, especially in commercial aquaculture. The studies performed so far have given the clear interaction between food, feeding and diets especially for the crustacean group, such being graphically explained in the graphical abstract.

Supplementary Materials: All data was placed along with the published paper

Author Contributions: Writing—original draft preparation, M.A.A.A. and A.H.; writing—review and editing, M.N.A.; supervision, M.N.N. and M.I.; funding acquisition, M.I.; conceptualization and methodology, M.A.A.A., M.N.N. and M.I.; data curation, M.N.A.; All authors have read and agreed to the published version of the manuscript.

Funding: This review was funded by the Ministry of Higher Education under the Higher Institution Center of Excellence (HiCoE) grant for development of future food through sustainable shellfish aquaculture.

Acknowledgments: We acknowledge all the staff at Institute of Tropical Aquaculture and Fisheries, Institute of Marine Biotechnology and Central Laboratory of Universiti Malaysia Terengganu who involved directly or indirectly to this review paper.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Aaqillah-Amr, M.A.; Hidir, A.; Noordiyana, M.N.; Ikhwanuddin, M. Morphological, biochemical and histological analysis of mud crab ovary and hepatopancreas at different stages of development. Anim. Rep. Sci. 2018, 195, 274-283. https://doi.org/10.1016/j.anireprosci.2018.06.005.

2. Hidir, A.; Aaqillah-Amr, M.A.; Noordiyana, M.N.; Ikhwanuddin, M. Diet and internal physiological changes of female orange mud crabs, Scylla olivacea (Herbst, 1796) in different ovarian maturation stages. Anim. Rep. Sci. 2018, 195, 216-229. https://doi.org/10.1016/j.anireprosci.2018.05.026.

3. Redzuari, A.; Azra, M.N.; Abol-Munaфи, A.B.; Aizam, Z.A.; Hii, Y.S.; Ikhwanuddin, M. Effects of feeding regimes on survival, development and growth of blue swimming crab, Portunus pelagicus (Linnaeus, 1758) larvae. World Appl. Sci. J. 2012, 18(4), 472–478. DOI: 10.5829/idosi.wasj.2012.18.04.313.

4. Abol-Munaфи, A.B.; Mukrim, M.S.; Amin, R.M.; Azra, M.N.; Azmie, G.; Ikhwanuddin, M. Histological profile and fatty acid composition in hepatopancreas of blue swimming crab, Portunus pelagicus (Linnaeus, 1758) at different ovarian maturation stages. Turkish J. Fish. Aquat. Sci. 2016, 16, 251–258. http://doi.org/10.4194/1303-2712-v16_2_04.

5. Taufik, M.; Bachok, Z.; Azra, M.N.; Ikhwanuddin, M. Effects of various microalgae on fatty acid composition and survival rate of the blue swimming crab Portunus pelagicus larvae. Induat J Mar Sci. 2016, 45 (11), 1512-1521. http://nopr.nisc.ac.in/bitstream/123456789/38612/1/IJMS%2045%2811%29%201512.pdf.

6. Ikhwanuddin, M.; Azmie, G.; Nahar, S.F.; Wee, W.; Azra, M.N.; Abol-Munaфи, A.B. Testis maturation stages of mud crab (Scylla olivacea) broodstock on different diets. Sains Malais. 2018, 47, 427-432. http://dx.doi.org/10.17576/jsm-2018-4703-01.

7. Pandey, G. Feed formulation and feeding technology for fishes. Int. Res. J. Pharm. 2013, 4(3), 23-30. DOI: 10.7897/2230-8407.04306.

8. Zettl, S.; Cree, D.; Soleimani, M.; Tabil, L.; Yildiz, F. Mechanical properties of aquaculture feed pellets using plant-based proteins. Cogent Food & Agriculture 2019, 5(1), 1656917. https://doi.org/10.1080/23311932.2019.1656917.

9. Al-Souti, A.; Gallardo, W.; Claereboudt, M.; Mahgoub, O. Attractability and palatability of formulated diets incorporated with chicken feather and algal meals for juvenile gilthead seabream, Sparus aurata. Aquac. Rep. 2019, 14, 100199. https://doi.org/10.1016/j.acrep.2019.100199.
10. Watts, S.A.; Lawrence, A.L.; Lawrence, J.M. Nutrition. Sea Urchins: Biology and Ecology, 2020, 191–208. https://doi.org/10.1016/B978-0-12-819570-3.00010-X.

11. D’Abramo, L.R. Challenges in developing successful formulated feed for culture of larval fish and crustaceans. Memorias del VI Simposio Internacional de Nutrición Acuícola, 2002, pp: 143-149.

12. Paulraj, R. Handbook on Aquafarming: Aquaculture Feed. Manual, 1993. MPEDA, Cochin.

13. ADCP (Aquaculture Development and Coordination Programme), 1983. Fish feeds and feeding in developing countries—an interim report on the ADCP Feed Development Programme. UNDP/FAO, Aquaculture Development and Coordination Programme, Rome, ADCP/REP/83/18: 97 pp.

14. Marsden, G.E.; McGuren, J.J.; Hansford, S.W.; Burke, M.J. A moist artificial diet for prawn broodstock: its effect on the variable reproductive performance of wild caught Penaeus monodon. Aquac. 1997, 149, 145 – 156.

15. Alloui, A.; Wille, M.; Lucenti, P.; Bossier, P.; Stapen, G.V.; Vlaeminck, S.E. Purple bacteria as added-value protein ingredient in shrimp feed: Penaeus vannamei growth performance, and tolerance against Vibrio and ammonia stress. Aquac. 2021, 530, 735788. doi:10.1016/j.aquaculture.2020.735788.

16. Samocha, T.M.; Patnaik, S.; Davis, D.A.; Bullis, R.A.; Browdy, C.L. Use of commercial fermentation products as a highly unsaturated fatty acid source in practical diets for the Pacific white shrimp Litopenaeus vannamei. Aquac. Res. 2010, 41, 961 – 967. https://doi.org/10.1111/j.1365-1319.2009.02378.x.

17. Gonzalez-Galaviz, J.R.; Casillas-Hernández, R.; Flores-Perez, M.B.; Lares-Villa, F.; Bórquez-López, R.A.; Gil-Núñez, J.C. Effect of genotype and protein source on performance of Pacific white shrimp (Litopenaeus vannamei). Ital. J. Anim. Sci. 2020, 19(1), 289 – 294. https://doi.org/10.1080/1828051X.2020.1733444.

18. Velasco, M.; Lawrence, A.L.; Neill, W.H. Development of a static-water ecoassay with microcosm tanks for postlarval Penaeus vannamei. Aquac. 1998, 161, 79 – 87.

19. Olalde, L.G.; Divakaran, S.; Tacon, A.G. Method for determining the physical stability of shrimp feeds in water. Aquac. Res. 2002, 33, 369 – 377.

20. Suresh, A.V.; Kumaraguru-vasagam, K.P.; Nates, S. Attractability and palatability of protein ingredients of aquatic and terrestrial animal origin, and their practical value for blue shrimp, Litopenaeus stylirostris fed diets formulated with high levels of poultry byproduct meal. Aquac. 2011, 319, 132 – 140. https://doi.org/10.1016/j.aquaculture.2011.06.039.

21. Derby, C.D.; Elsayed, F.H.; Williams, S.A.; González, C.; Choe, M.; Bharadwaj, A.S.; Chamberlain, G.W. Krill meal enhances performance of feed pellets through concentration-dependent prolongation of consumption by Pacific white shrimp, Litopenaeus vannamei. Aquac. 2016, 458, 13 – 20. https://dx.doi.org/10.1016/j.aquaculture.2016.02.028.

22. Gamboa-Delgado, J.G.; Morales-Navarro, Y.I.; Nieto-López, M.G.; Villarreal-Cavazos, D.A.; Cruz-Suárez, L.E. Assimilation of dietary nitrogen supplied by fish meal and microalgal biomass from Spirulina (Arthrospira platensis) and Nannochloropsis oculata in shrimp Litopenaeus vannamei fed compound diets. J. Appl. Physiol. 2019, 31, 2379 – 2389, https://doi.org/10.1007/s10811-019-1738-2.

23. Martínez-Rocha, L.; Gamboa-Delgado, J.; Nieto-López, M.; Ricque-Marie, D.; Cruz-Suárez, L.E. Incorporation of dietary nitrogen from fish meal and pea meal (Pisum sativum) in muscle tissue of Pacific white shrimp (Litopenaeus vannamei) fed low protein compound diets. Aquac. Res. 2012, 1 – 13. https://doi.org/10.1111/j.1365-2109.2011.03083.x.

24. Fang, X.; Yu, D.; Buentello, A.; Zeng, P.; Davis, D.A. Evaluation of new non-genetically modified soybean varieties as ingredients in practical diets for Litopenaeus vannamei. Aquac. 2016, 451, 178 – 185. 10.1016/j.aquaculture.2015.08.026.

25. Palma, J.; Bureau, J.; Andrade, P. Effects of binder type and binder addition on the growth of juvenile Penaeus monodon and Palaemon elegans (Crustacea: Palaemonidae). Aquac. Int. 2008, 16, 427 – 436. https://doi.org/10.1007/s10499-007-9155-5.

26. Park, E.D.; Lightner, D.V.; Williams, R.R.; Mohney, L.L.; Stamm, J.M. Evaluation of difloxacin for shrimp aquaculture: In vitro minimum inhibitory concentrations, medicated feed palatability, and toxicity to the shrimp Penaeus vannamei. J. Aquat. Anim. Health 1995, 7(2), 161 – 167, https://doi.org/10.1575/1548-8667(1995)007<0161:EODFSA>2.3.CO;2.

27. Thang, N.D.; Tu, L.D.; Na, N.T.L.; Trang, N.T.; Nghia, P.T. Melanin-containing featherstuffs protect Litopenaeus vannamei from white spot syndrome virus. Int. Aquac. Res. 2019, 11, 303 – 310. https://doi.org/10.4007/0071-01992007-00240-4.

28. Gil-Núñez, J.C.; Martínez-Córdova, L.R.; Servin-Villegas, R.S.; Magallon-Barajas, F.J.; Bórquez-López, R.A.; Gonzalez-Galaviz, J.R.; Casillas-Hernández, R. Production of Penaeus vannamei in low salinity, using diets formulated with different protein sources and percentages. Lat. Am. J. Aquat. Res. 2020, 48(3), 396 – 405. https://doi.org/10.3856/vol48-issue3-fulltext-2361.

29. Galkanda-Arachchige, H.S.C.; Guo, J.; Stein, H.H.; Davis, D.A. Apparent energy, dry matter and amino acid digestibility of differently sourced shrimp meal fed to Pacific white shrimp Litopenaeus vannamei. Aquac. Res. 2019, 51, 326 – 340. https://doi.org/10.1111/are.14378.

30. Tazikah, T.; Kenari, A.A.; Esmaeili, M. Effects of fish meal replacement by meat and bone meal supplemented with garlic (Allium sativum) powder on biological indices, feeding, muscle composition, fatty acid and amino acid profiles of whiteleg shrimp (Litopenaeus vannamei). Aquac. Res. 2019, 51, 674 – 686. https://doi.org/10.1111/are.14416.

31. Moniruzzaman, M.; Damusaru, J.H.; Won, S.; Cho, S.J.; Chang, K.H.; Bai, S.C. Effects of partial replacement of dietary fish meal by bioprocessed plant protein concentrates on growth performance, hematology, nutrient digestibility and digestive enzyme activities in juvenile Pacific white shrimp, Litopenaeus vannamei. J. Sci. Food Agric. 2019, 100, 1285 – 1293. https://doi.org/10.1002/jsfa.10141.

32. Ruscoe, I.M.; Jones, C.M.; Jones, P.L.; Caley, P. The effects of various binders and moisture content on pellet stability of research diets for freshwater crayfish. Aquac. Nutr. 2005, 11, 87 – 93.

33. Thompson, K.R.; Muzinic, L.A.; Christian, T.D.; Webster, C.D. Effect on growth, survival, and fatty acid composition of Australian red claw crayfish Cherax quadrirarinatus fed practical diets with and without supplemental lecithin and/or cholesterol. J. World Aquac. Soc. 2003, 34(1), 1 – 10.
34. Volpe, M.G.; Varricchio, E.; Coccia, E.; Santagata, G.; Di-Stasio, M.; Malinconico, M.; Paolucci, M. Manufacturing pellets with different binders: Effect on water stability and feeding response in juvenile Cherax albidus. *Aquac. 2012*, 324 – 325, 104 – 110. https://doi.org/10.1111/j.1365-1109.2011.02099.

35. Jussila, J.; Evans, L.H. Growth and condition of marron Cherax tenuimanus fed pelleted diets of different stability. *Aquac. Nutr. 1998*, 4, 143 – 149.

36. Ahamad-Ali, S.; Syama-Dayal, J.; Ambasankar, K. Presentation and evaluation of formulated feed for mud crab *Scylla serrata*. *Ind. J. Fish. 2011*, 58(2), 67 – 73.

37. Catacutan, M.R. Growth and body composition of juvenile mud crab, Scylla serrata, fed different dietary protein and lipid levels and protein to energy ratios. *Aquac. 2002*, 208, 113 – 123.

38. Zhao, J.; Wen, X.; Li, S.; Zhu, D.; Li, Y. Effects of dietary lipid levels on growth, feed utilization, body composition and antioxidants of juvenile mud crab Scylla paramamosain (Estampador). *Aquac. 2015*, 435, 200 – 206. http://dx.doi.org/10.1016/j.aquaculture.2014.09.018.

39. Zhao, J.; Wen, X.; Li, S.; Zhu, D.; Li, Y. Effects of different dietary lipid sources on tissue fatty acid composition, serum biochemical parameters and fatty acid synthase of juvenile mud crab *Scylla paramamosain* (Estampador) 1949). *Aquac. Res. 2016*, 47, 887 – 899, https://doi.org/10.1111/are.12547.

40. Unnikrishnan, U.; Chakraborty, K.; Paulraj, R. Efficacy of various lipid supplements in formulated pellet diets for juvenile *Scylla serrata*. *Aquac. Res. 2010*, 41, 1498 – 1513. https://doi.org/10.1111/j.1365-2109.2009.02443.x.

41. Unnikrishnan, U.; Paulraj, R. Dietary protein requirement of giant mud crab *Scylla serrata* juveniles fed iso-energetic formulated diets having graded protein levels. *Aquac. Res. 2010*, 41, 278 – 294. https://doi.org/10.1111/j.1365-2109.2009.02330.x.

42. Sheen, S.S.; Wu, S.W. The effects of dietary lipid levels on the growth response of juvenile mud crab *Scylla serrata*. *Aquac. 1999*, 175, 143 – 153.

43. Sheen, S.S. Dietary cholesterol requirement of juvenile mud crab *Scylla serrata*. *Aquac. 2000*, 189, 277 – 285.

44. Sheen, S.S.; Wu, S.W. Essential fatty acid requirements of juvenile mud crab, *Scylla serrata* (Forskal, 1775) (Decapoda, Scyllariidae). *Cristacea 2002*, 75(11), 1387 – 1401. http://www.jstor.org/stable/210552.

45. Marchese, G.; FitzGibbon, Q.P.; Trotter, A.J.; Carter, C.G.; Jones, C.M.; Smith, G.G. The influence of flesh ingredients format and krill meal on growth and feeding behaviour of juvenile tropical spiny lobster *Panulirus ornatus*. *Aquac. 2019*, 499, 128 – 139. https://doi.org/10.1016/j.aquaculture.2018.09.019.

46. Bryars, S.R.; Geddes, M.C. Effects of diet on the growth, survival, and condition of sea-caged adult southern rock lobster, *Jasus edwardsii*. *N. Z. J. Mar. Freshwater Res. 2005*, 39(2), 251 – 262. https://doi.org/10.1080/002873205.9517305.

47. Saleela, K.N.; Somanath, B.; Palavesam, A. Effects of binders on stability and palatability of formulated dry compounded diets for spiny lobster *Panulirus homarus* (Linnaeus, 1758). *Indian J. Fish. 2015*, 62(1), 95 – 100.

48. Perera, E.; Fraga, I.; Carillo, O.; Díaz-Iglesias, E.; Cruz, R.; Báez, M.; Galich, G.S. Evaluation of practical diets for the Caribbean spiny lobster *Panulirus argus* (Latreille, 1804): Effects of protein sources on substrate metabolism and digestive proteases. *Aquac. 2005*, 244, 251 – 262. https://doi.org/10.1016/j.aquaculture.2004.11.022.

49. Simião, C.D.S.; Colombo, G.M.; Schmitz, M.J.; Ramos, P.B.; Tesser, M.B.; Jr., W.W.; Monserrat, J.M. Inclusion of Amazonian *Mauritia flexuosa* fruit pulp as functional feed in the diet for the juvenile Pacific white shrimp *Litopenaeus vannamei*. *Aquac. Res. 2019*, 51, 1731 – 1742. https://doi.org/10.1111/are.14520.

50. Alava, V.R.; Quintino, E.T.; dePedro, J.B.; Orosco, Z.G.A.; Wille, M. Reproductive performance, lipids and fatty acids of mud crab *Scylla serrata* (Forskål’s) fed dietary lipid levels. *Aquac. Res. 2007*, 38, 1442 – 1451. https://doi.org/10.1111/j.1365-2109.2007.01722.x.

51. Aas, T.S.; Oehme, M.; Sørensen, M.; He, G.; Lygren, I.; Åsgård, T. Analysis of pellet degradation of extruded high energy fish feeds with different physical qualities in a pneumatic feeding system. *Aquacult. Eng. 2011*, 44, 25-34. https://doi.org/10.1016/j.aquaeng.2010.11.002.

52. Mohamad-Yazid, N.S.; Abdullah, N.; Muhammad, N.; Matias-Peralta, H.M. Application of starch and starch-based products in food industry. *J. Sci. Tech. 2018*, 10(2), 144 - 174. https://publisher.uthm.edu.my/ois/index.php/JST/article/view/3022.

53. Rokey, G.J.; Plattner, B.; deSouza, E.M. Feed extrusion process description. *Rev. Bras. de Zootec.* **2010**, 39, 510-518. DOI: 10.1590/S1516-35982010001300055.

54. Nizza, A.; Piccolo, G. Chemical-nutritional characteristics of diets in marine aquaculture. *Vet. Res. Commun.* **2009**, 33(S1), 25-30. DOI: 10.1007/s11259-009-9240-5.

55. Hasan, M.R. Nutrition and feeding for sustainable aquaculture development in the third millennium. In Aquaculture in the Third Millennium, Technical Proceedings of the Conference on Aquaculture in the Third Millennium, Bangkok, Thailand, 20-25 February 2000; R.P. Subasinghe, P. Bueno, M.J. Phillips, C. Hough, S.E. McGladdery & J.R. Arthur, eds.; NACA, Bangkok and FAO, Rome, 2001; pp. 193-219.

56. Solomon, S.G.; Ataguba, G.A.; Abeje, A. Water stability and floatation test of fish pellets using local starch sources and yeast (*Saccharomyces cerevisiae*). *Int. J. Latest Trends Agric. Food Sci. 2011*, 1, 1-5.

57. Paolucci, M.; Fasulo, G.; Volpe, M.G. Employment of marine polysaccharides to manufacture functional biocomposites for aquaculture feeding applications. *Mar. Drugs* **2015**, 13, 2680-2693. doi: 10.3390/md13052680.

58. Banjac, V.V.; Colovic, R.R.; Pezo, L.L.; Ćolović, D.S.; Gubić, J.M.; Duragic, O.M. Conductometric method for determining water stability and floatation test of fish pellets using local starch sour. *Aquaculture Nutr*., **2015**, 21, 1-12. https://doi.org/10.1111/anu.12315.

59. Sudaryono, A. Pellet water stability studies on lupin meal based shrimp (*Penaeus monodon*) aquaculture feeds: Comparison of lupin meal with other dietary protein sources. *J. Coast. Dev.* **2001**, 4(3), 129-140.
60. Felix, E.; Oscar, E.V. Floating and stability effect on fish feed pellets using different concentration of baobab leaf meal (*Adansonia digitata*). *Asian J. Fish. Aquat. Res.* 2018, 1(4), 1-6. https://doi.org/10.9734/ajar/2018/v1i4348.

61. Onada, O.; Ogunola, O. Comparative analysis of sinking time index and water stability of different level of inclusion of cassava flour and brewer yeast in a test diet. *Int. J. Eng. Res. 2019*, 10(5), 1251-1265.

62. Orie, A.M.; Emine, G.I. Effects of crude protein levels and binders on feed buoyancy. *J. Aquac. Res. Dev.* 2019, 10(2), 565. 10.4172/2155-9546.1000565.

63. Abubakar, M.Y.; Momoh, A.T.; Ipinjolu, J.K. Effect of pelletizing machines on floatation and water stability of farm-made fish feeds. *Int. J. Fish. Aquat. Stud.* 2016, 4(3), 98-103.

64. Momoh, A.T.; Abubakar, M.Y.; Ipinjolu, J.K. Effect of ingredients substitution on binding, water stability and floatation of farm-made fish feed. *Int. J. Fish. Aquat. Stud.* 2016, 4(3), 92-97.

65. Bandyopadhyay, S.; Rout, R.K. Aquafeed extrudate flow rate and pellet characteristics from low-cost single-screw extruder. *J. Aquat. Food Prod. Technol.* 2001, 10(2), 3-15. https://doi.org/10.3390/md17030151

66. Ighwela, K.A.; Ahmad, A.; Abol-Munafi, A.B. Water stability and nutrient leaching of different levels of maltose formulated fish pellets. *Glob. Vet.* 2013, 10(6), 638-642.

67. Lwin, M.M.N. Development of diets for soft-shell mangrove crabs (*Scylla* spp.). Doctoral dissertation, University of Auburn, Alabama. 2018. http://hdl.handle.net/10415/6069.

68. Azra, M.N.; Ikhanwuddin, M. A review of maturation diets for mud crab genus *Scylla* broodstock: Present research, problems and future perspective. *Saudi J. Biol. Sci.* 2016, 23(2), 257-267. http://dx.doi.org/10.1016/j.sjbs.2015.03.011.

69. Holme, M.H.; Zeng, C.; Southgate, P.C. A review of recent progress toward development of a formulated microbound diet for mud crab, *Scylla serrata*, larvae and their nutritional requirements. *Aquac. 2009*, 286, 164-175. https://doi.org/10.1016/j.aquaculture.2008.09.021.

70. Islam, M.L.; Yahya, K. Successive reproductive performance and amino acid profiles in the newly hatched larvae of green mud crab (*Scylla paramamosain*) under captive condition. *Int. J. Fish. Aquat. Stud.* 2016, 4(5), 270-279.

71. Ayisi, C.L.; Hua, X.; Apraku, A.; Afriyie, G.; Kyei, B.A. Recent studies toward the development of practical diets for shrimp and their nutritional requirements. *HAYATI J. Biosci.* 2017, 24(3), 109-117. https://doi.org/10.1016/j.hjb.2017.09.004.

72. Zheng, F.; Han, T.; Li, X.; Wang, J.; Su, H.; Xu, X.; Wang, Y.; Wang, C. Dietary protein requirement of juvenile mud crab *Scylla paramamosain*. *Aquac. 2020*, 515, 734852. https://doi.org/10.1016/j.aquaculture.2019.734852.

73. Weiss, M.; Rebeline, A.; Slater, M.J. Lupin kernel meal as fishmeal replacement in formulated feeds for the Whiteleg Shrimp (*Litopenaeus vannamei*). *Aquac. Nutr.* 2019, 26, 752 – 762. https://doi.org/10.1111/anu.13034.

74. Wang, X.; Jin, M.; Cheng, X.; Hu, X.; Zhao, M.; Yuan, Y.; Sun, P.; Jiao, L.; Betancor, M.B.; Tocher, D.R.; Zhou, Q. Dietary DHA/EPA ratio affects growth, tissue fatty acid profiles and expression of genes involved in lipid metabolism in mud crab *Scylla paramamosain* supplied with appropriate n-3 LC-PUFA at two lipid levels. *Aquac. 2021*, 532, 736028. https://doi.org/10.1016/j.aquaculture.2020.736028.

75. Fernandis, A.Z.; Wenk, M.R. Membrane lipids as signalling molecules. *Curr. Opin. Lipidol.* 2007, 18(2), 121-128. 10.1097/MOL.0b013e328085e4d5.

76. Hamre, K.; Yüfera, M.; Romanestad, I.; Boglione, C.; Conceição, L.E.C.; Izquierdo, M. Fish larval nutrition and feed formulation: knowledge gaps and bottlenecks for advances in larval rearing. *Rev. Aquac.* 2013, 5(s1), S26 – S58. https://doi.org/10.1111/j.1753-1511.2012.01086.x.

77. Kumar, V.; Sinha, A.K.; Romano, N.; Allen, K.M.; Bowman, M.A.; Thompson, K.R.; Tidwell, J.H. Metabolism and nutritive role of cholesterol in the growth, gonadal development, and reproduction of crustaceans. *Rev. Fish. Sci. Aquac.* 2018, 26(2), 254-273. https://doi.org/10.1080/23308249.2018.1429384.

78. Jerez, S.; Rodríguez, C.; Cejas, J.R.; Bolaños, A.; Lorenzo, A. Lipid dynamics and plasma level changes of 17-β-estradiol and testosterone during the spawning season of gillhead seabream (*Sparus aurata*) females of different ages. *Comp. Biochem. Physiol. B 2006*, 143, 180-189. https://doi.org/10.1016/j.cbpb.2005.11.002.

79. Jónasdóttir, S.H. Fatty acid profiles and production in marine phytoplankton. *Mar. Drugs* 2019, 17(3),151. doi: 10.3390/md17030151.

80. Brett, M.T.; Müller-Navarra, D.C. The role of highly unsaturated fatty acids in aquatic foodweb processes. *Freshw. 1997*, 38, 483–499.

81. Anido, R.V.; Zaniboni-Filho, G.; Garcia, A.S.; Baggio, S.R.; Fracalossi, D.M. Characterization of the ovary fatty acids composition of *Rhamdia quelen* (Quoy & Gaimard) (Teleostei: Siluriformes), throughout their reproductive cycle. *Neopt. Ichthylol, 2015*, 13(2), 453 - 460. https://doi.org/10.1590/1982-0224-201401039.

82. Strobel, C.; Jahreis, G.; Kuhn, K. Survey of n-3 and n-6 polyunsaturated fatty acids in fish and fish products. *Lipids Health Dis. 2012*, 11(1), 144. doi: 10.1186/1476-511X-11-144.

83. Chen, C.; Guan, W.; Xie, Q.; Chen, G.; He, X.; Zhang, H.; Guo, W.; Chen, F.; Tan, Y.; Pan, Q. n-3 essential fatty acids in Nile tilapia, *Oreochromis niloticus*: Bioconverting LNA to DHA is relatively efficient and the LC-PUFA biosynthetic pathway is substrate limited in juvenile fish. *Aquac.* 2018, 495, 513-522. https://doi.org/10.1016/j.aquaculture.2018.06.023.