Review

Importance of Interactions between Food Types and Feeding Behavior in Diet Formulation for Crustaceans: A Review

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Simple Summary: Various crustacean species respond differently to both types of food and methods of feeding, with different feeding behaviors, and there is a lack of published literature available to support diet formulation. This review explains the interactions between food, feeding, and diets in crustaceans. Pellet physical characteristics and nutritive values, and feeding behavior, are important to improve production of aquaculture species, especially crustaceans. Updated knowledge of these aspects will enhance future commercialization of seafood production.

Abstract: A number of studies have investigated different crustacean food stuffs, feeding methods, and feeding behavior, but little attention has been given to the interaction between these aspects in crustaceans. The aim of the present review is to update knowledge, and examine challenges and opportunities in the development of formulated diets, as pelleted feed, which is vital for developing better quality of seed or broodstock in hatcheries, and adaptation of hatchery product to the aquaculture environment, and production systems.

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 since feeds consumed the largest operational cost in the crustacean hatchery [1]. The development of pellet diets or aquafeed for aquaculture species is of intense, current interest, as pellets offer many advantages in comparison with 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 of crustacean, a formulated feed can be expected to provide sufficient nutrition to broodstock. Currently, no commercial broodstock diet is available for some crustacean species [2, 3]. So the standard diets for crustacean broodstock were of commercial shrimp pellets [3 – 5]. There are not much published studies focused on formulating a feeding diet, particularly to some crustacean broodstock. This is probably because of the unique feeding behavior of each crustacean species such as carnivorous [6], slow feeder [7], and bottom dweller [8]. Several species are restricted to certain environments, reflected in aquaculture systems that give effect to the type of feeding selection [9 – 12].

The growing demand for animal protein from existing competition between human need and aquaculture feeding resulted in the decreasing of fish landings [13], since fish are the sole provider of n-3 PUFA in the diet. This adds to the existing gap between demand and supply for fish and fish products. Many studies have evaluated adjustments to aquaculture feeding formulation by reducing dependence on fish sources as the source of protein and lipid. Use of terrestrial animal proteins such as meat, poultry by-product, bone meal, and blood meal, as replacement for fish oil and fishmeal, has confirmed their efficiencies of replacements in providing the animals aquaculture species with good protein levels [14]. Use of protein sources from plant-based materials is gaining attention nowadays. Plant protein sources such as camelina meal, canola meal, and soybean meal can be used as substitutes for fish meal without imposing negative effects on growth and feed intake [15]. However, the major setbacks associated with the use of protein source from the terrestrial animals and plant origin include the lack attractants and palatability factors [16]. Compared to feed derived from aquatic animals such as fishmeal, shrimp meal, and squid meal, lack of attractants component may result in poor ingestion of feeds thus reducing the rate of feed intake and retarding growth in the cultured species [17].

In general, the physical form of the pellets will depend on the species being cultured. High moisture contents in the pellets is 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, partly because some species are aggressive in handling foods [18]. In addition, the proper storage and handlings of feed products may be difficult to manage, as is the case with wet pellet. Since the wet pellets have high moisture content, rapid spoilage such as mold problems, is unavoidable in long storage period [19, 20].

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%, and 15 – 25% for wet feeds, dry feeds, moist feeds, and semi-moist feeds respectively [21]. 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 [22].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).

Table 1: Crustacean's feed types with pellet and animal performances

Crusta-cean's Group	Type of feed(s)				Pellet performance			Animal performance			Reference
	Type of feed	Shape / size	Moist / Dry	Binding agent	Leaching / Stability	Acceptability / Palatability	Digestibility / Energy	Growth performance (GP)	PER	Feed Conversion Ratio (FCR)	
Prawn	Floating soft pellet	4 mm diameter strands	Moist	Floating soft pellet	Diets developed met the criteria of good water stability	Diets developed met the criteria of good attractive feed	N/A	Higher survival using formulated diet (fresh ingredient calf liver & artemia enrichment)	N/A	N/A	Marsden et al. (1997) [23]
Shrimp	Commercial pellet	Ground pellet (i) 300–1200 µm	Dry pellet	Carboxymethylcellulose (CMC)	N/A	N/A	N/A	Dietary inclusion of purple non-sulfur bacteria (PSNB) improved shrimp's GP	N/A	Shrimp fed with diets containing PSNB had higher FCR	Alloul et al. (2021) [24]
	Pressure (Extruded) pellet	2 mm	Dry pellet	Wheat starch, whole wheat	N/A	All diets readily consumed with no indication of feed rejection	N/A	Shrimp fed without HUFA supplements showed reduction in growth	N/A	FCR values of shrimp with HUFA's diet	Samocha et al. (2010) [25]
	Extruded pellet	N/A	Dry pellet	Wheat meal, corn starch	N/A	N/A	N/A	Fast growth (FG) shrimp genotype - higher growth rate than the high resistance (HR) shrimp genotype	N/A	Both FG & HR showed no feed efficiency differentiation (fed animal- or vegetable-based diet)	Gonzalez-Galavis et al. (2020) [26]
	Extruded pellet	0.5 mm diameter	Dry pellet	Wheat starch, wheat gluten	Higher feeding rate -	N/A	N/A	High variable feeding rate provided high Post-Larvae (PL) survival & growth	N/A	FCR of 0.85 with high variable feeding rate (VFR-high)	Velasco et al. (1998) [27]
	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	N/A	N/A	N/A	Obaldo et al. (2002) [28]
	Extruded pellet	Noodle-like	Dry pellet	Wheat flour, wheat gluten	Dry matter loss of the test feeds	Visible behavioral differences among shrimp	N/A	Shrimp fed krill meal registered maximum weight gain. >86%	N/A	No difference in FCR or yield	Suresh et al. (2011) [29]

	4 - 5 mm strands			ranged from 6.3 to 10.6%	were apparent immediately after access to the feed		survival in all treatments		among the various treatments	
Extruded pellet	3 mm × 5 mm strand	Dry pellet	Wheat flour	5-min leachate of intact pellet without any krill meal additive - strongest binder	Feed containing krill meal (as low as 1% up to 6%) enhanced ingestion of pellets	N/A	Krill meal effectively enhance growth (with chemostimulants - enhance palatability)	N/A	N/A	Derby et al. 2016) [30]
Extruded pellet	1.4 mm orifices strands	Dry pellet	Wheat starch	N/A	N/A	N/A	Final mean weight significantly higher when formulated with 50% fish meal & 50% Spirulina	N/A	N/A	Gamboa-Delgado et al. (2019) [31]
Commercial extruded compound pellet	Strands with die plate - 1.4 mm in diameter	Dry pellet	Wheat starch	N/A	N/A	N/A	Growth rates negatively correlated to dietary pea protein inclusion	N/A	N/A	Martínez-Rocha et al. (2012) [32]
Pressure (extruded) pellet	3 mm diameter pellet	Dry pellet	Whole wheat	N/A	Diets with fish meal to soybean meal replacement showed good feed palatability	Non-GM soy cultivars producing soybean meal show higher digestibility compared to white flakes or pressed soy cakes	The diet incorporating ingredient-17 (soybean meal; dehulled, roasted, hexane-extracted and ground) showed largest weight gain	N/A	N/A	Fang et al. (2016) [33]
Sinking pellet	3 mm pellets	Steam pellet	Lignosol, agar	Higher dry matter loss in pellet with binder lignosol	All pellets were readily consumed by the shrimps	N/A	Weight gain (WG) higher for *Palaemon elegans* than *Palaemonetes varians* fed diets with lignosol added by microbinding diet		FCR was higher for *P. elegans* compared to *P. varians*	Palma et al. (2008) [34]

					through micro coating						
	Extruded feed	3 mm diameter pellet	Dry pellet	Aquabind	N/A	Difloxacin was palatable at the 1× treatment level (100 mg/kg of feed)	N/A	Mean weight gains by animals receiving difloxacin did not correlate with feed consumption	N/A	FCR were higher in shrimps fed difloxacin-medicated diets	Park et al. (1995) [35]
	Commercial pellet	Bead form with a diameter of 2 mm	Dry pellet	Cod oil, starch solution (3%), squid ink-sac liquid	The melanin coated with starch solution was strongly bound inside the feed	N/A	N/A	Melanin coated starch solution and melanin coated fish oil had protection rates of 57% and 67% at Day 7 respectively	N/A	N/A	Thang et al. (2019) [36]
	Extruded pellet	N/A	Dry pellet	Wheat flour, corn starch	N/A	N/A	N/A	Shrimp fed diets formulated fish meal (FM) significantly higher WG & specific growth rate (SGR)	Shrimp fed diets formulated with FM significantly higher PER	No significant difference between protein sourced from fish meal and soy meal	Gil-Nunez et al. (2020) [37]
	Extruded	3 mm diameter pellet	Dry pellet	Whole wheat, corn starch	N/A	N/A	Higher apparent digestibility of dry matter, energy, protein	Increased protein & energy digestibility of an ingredient contribute to higher growth performance	N/A	N/A	Galkanda-Arachchige et al. (2019) [38]
	Steam pellet	1 mm diameter pellet	Dry pellet	CMC	N/A	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	High PER was recorded in feeds supplemented with meat & bone meal with garlic	Highest FCR was recorded in feeds supplemented with 50% meat & bone meal with garlic	Tazikeh et al. (2019) [39]
	Steam pellet	N/A	Dry pellet	CMC	N/A	N/A	Apparent digestibility of feeds & ingredients higher in fish fed the	Shrimp fed the bioprocessed protein concentrates significantly higher growth performance at 30% fish meal replacement	Shrimp fed the bioprocessed protein concentrates showed significantly higher PER	Shrimp fed the bioprocessed protein concentrates showed significantly higher feed efficiency (FE)	Moniruzzaman et al. (2019) [40]

							bioprocessed protein				
Crayfish	Steam sinking pellet	5 mm diameter conglomerated structured	Moist pellet	Carrageenan, Cardoxymethyl-cellulose (CMC), agar & gelatine	5% binder retained more dry matter compared to 3% binder	N/A	N/A	N/A	N/A	N/A	Ruscoe et al. (2005) [41]
	Extruded pellet	1 cm diameter spaghetti like structure	Dry pellet	Carboxymethylcellulose (CMC)	N/A	Some redclaw fed Diet 3 (0% cholesterol and 0.5% lecithin) did not appear to aggressively consume the diet efficiently	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	N/A	Thompson et al. (2003) [7]
	Extruded Pellet	1cm × 0.1 cm diameter with Spaghetti into cylindrical from	Dry pellet	Pectin, alginate & chitosan	Pectin diet showed good water stability	N/A	N/A	Pectin diet showed highest wet gain	Pectin diet shows better PER	Chitosan diet showed highest FCR	Volpe et al. (2012) [42]
	Extruded pellet (Stable and unstable pellet)	N/A	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	N/A	N/A	Jussila & Evans (1998) [43]
Crab	Steam pellet	1 cm diameter; compounded feed (ball form and pellet form)	Semi-Moist & dry pellet	Poly Methylol Carbamide	Semi-moist ball feed showed higher dry matter loss (30.4%) during feeding	Crabs showed excellent acceptance of the feeds	N/A	Crab fed with dry feeds showed highest weight gain	N/A	Crabs fed formulated diets showed better feed gain ratio (FGR) than the crabs fed trash fish	Ahamad-Ali et al. (2011) [44]

	Steam pellet	Strands pellet with 3 - 5 mm length	Dry pellet	CMC	N/A	N/A	14.7-17.6 MJ/kg	Crabs grow well when fed diets containing 32-40% protein with either 6 or 12% lipid	20.5-31.1 mg protein/ kJ	The FCR, intermolt duration and total number of days of feeding test diets were not affected by dietary treatments	Catacutan (2002) [45]
	Extruded pellet	4-6 mm length	Dry pellet	Tapioca starch	N/A	Voluntary feed intake in crabs may increase the intake of low-lipid diet which were higher at 6% lipid	N/A	Maximum SGR is obtained when the diets are supplemented with 6.57% oil	The highest feed conversion ratio was observed in crabs at 6% lipid feed	Lowest protein efficiency ratio was observed in crabs at 6% lipid feed	Zhao et al. (2015) [46]
	Extruded pellet	4-6 mm length	Dry pellet	Dextrin	N/A	N/A	N/A	Pelleted diet with fish oil or mixture oil - higher survival	N/A	N/A	Zhao et al. (2016) [47]
	Steam pellet	1.2 mm diameter; 4.0 mm length	Dry pellet	Guar gum	Pellets showed higher water stability after 4 hours of immersion	Crabs showed good voluntary feed intake of the feeds (mixed oil refer as vegetables oil + cod liver oil)	Higher apparent digestibility recorded in diets from mixed oil	Crabs fed with mixed oil recorded the same SGR with crabs fed with cod liver oil alone	Similar PER value (1.44 to 1.46) for mixed oil comparable with cod liver oil alone	Similar FCR recorded for crabs fed with mixed oil and cod liver oil alone	Unnikrishnan et al. (2010) [48]
	Steam pellet	~1.2 mm diameter; 4.0 mm length	Dry pellet	Guar gum	Pellets showed higher water stability in all feeds	The crabs fed with CP-20 (20% dietary protein) showed the lowest voluntary feed intake (VFI)	Lower apparent digestibility of protein	The best growth performance as well as the nutrient turn-over was recorded in crabs fed with 45% crude protein in the diet	The highest PER was obtained by feeding the crabs with CP-20, a	The FCR was found to decrease with an increasing dietary protein level up to 45% (CP45)	Unnikrishnan & Paulraj (2010) [49]
	Steam pellet	1×1×0.3 cm jelly cubes	Moist pellet	Agar-agar	N/A	N/A	N/A	Crabs fed diets supplemented with 0 and 2% oil mixture had lower weight gain	N/A	N/A	Sheen & Wu (1999) [50]
	Steam pellet	1×1×0.3 cm jelly cubes	Moist pellet	Agar-agar	N/A	N/A	N/A	Crabs fed the diets containing 0.5 and 0.79% cholesterol had higher weight gain	N/A	N/A	Sheen (2000) [51]

								whereas 1.12% cholesterol had an adverse effect on mud crab growth			
	Steam pellet	1×1×0.3 cm jelly cubes	Moist pellet	Agar-agar	N/A	N/A	N/A	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	N/A	N/A	Sheen & Wu (2002) [52]
Lobster	Steam pellet	5 - 9 mm cylindrical rod pellet	Moist pellet	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. (2019) [53]
	Steam pellet	10 - 20 mm length passed through 4 mm diameter die	Dry pellet	Aquabind	N/A	N/A	N/A	Equivalent growth for all trial lobster	N/A	Higher feed supplied conversion ratios of pellet-fed treatments	Bryars & Geddes (2005) [54]
	Steam pellet	4 mm diameter	Dry pellet	Tapioca powder, agar-agar, 'stick on' a phytochemical, gum Arabic, guar gum, wheat flour, gelatin, and	Basal diets with binders in performed the highest stability compared to other binder combination	Lobster showed good acceptance of basal diets and palatability as recorded through behavior	N/A	N/A	N/A	N/A	Saleela et al. (2015) [8]

	Stream pellet	String size	Dry pellet	sodium alginate Carboxymethylcellulose	Leaching of nutritional components accrediting 30 minutes	Diets were immediately ingested by lobster in first 30 minutes	Feed with squid meal increase nutritional value & enhances digestive activity	N/A	Supplement of high-quality local fish / squid meal increase protein efficiency	N/A	Perera et al. (2005) [55]

*N/A: Not available

Table 2: Crustacean's feeding behaviour and life stages

Crustacean's group	Species	Life history stage	Feeding behavior			Reference
			Feeding habit	Feeding rate	Feeding time	
Shrimp	*Litopenaeus vannamei*	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. (2016) [30]
	Palaemonetes varians and P. elegans	Juvenile	Shrimps are slow and continuous eaters	10% body weight	Fed once a day in the morning (10:00 h)	Palma et al. (2008) [34]
	Penaeus vannamei	Juvenile	N/A	5% of cumulative animal body weight per tank	Once per day in the morning	Park et al. (1995) [35]
	Litopenaeus vannamei	Juvenile	N/A	Fed in excess	Animals were fed four times per day	Galkanda-Arachchige et al. (2019) [38]
	Litopenaeus vannamei	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. (2019) [31]; Moniruzzaman et al. (2019) [40]
	Penaeus vannamei	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. (2020) [37]
	Litopenaeus vannamei	Juvenile	N/A	7% average body weight	Fed twice daily (08:00 and 17:00)	Simião et al. (2019) [56]
Crayfish	*Cherax quadricarinatus*	Juvenile	Slow feeding response	Fed to excess	Fedthree times daily (0730, 1230, and 1600 h)	Thompson et al. (2003) [7]
	Cherax albidus	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. (2012) [42]
	Cherax tenuimanus	Juvenile	Slow intake, prolonged handling, long intervals between food intakes	6.5% body weight	Feed daily	Jussila & Evans (1998) [43]
Crab	*Scylla serrata*	Immature / Mature	Omnivorous scavengers, opportunistic feeder; crabs approach and grab feeds with chelae	10% body weight	Fed twice; 11 am& 4pm	Ahamad-Ali et al. (2011) [44]

	Scylla serrata	Juvenile	Show preference for detritus	Fed to satiation (about 2 - 3.5% body weight)	Fed twice daily at satiation level	Catacutan (2002) [45]
	Scylla paramamosain	Juvenile	N/A	Fed with excess diets	Fed twice a day at 8:00 hours and 18:00 hours	Zhao et al. (2016) [47]
	Scylla serrata	Juvenile	N/A	6% body weight	Fed twice daily (at 07:00 hrs and 17:00 hrs)	Unnikrishnan et al. (2010) [48]; Unnikrishnan & Paulraj (2010) [49]
	Scylla serrata	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. (2007) [57]
Lobster	*Panulirus ornatus*	Juvenile	Cannibalistic ; rely on chemoreception; slow feeder	50% body weight	Fed twice daily (morning and afternoon)	Marchese et al. (2019) [53]
	Panulirus argus	Juvenile	Opportunistic predator	Lobster fed at a rate below that required level to reach satiation (2% of lobster wet weight)	Fed twice daily	Perera et al. (2005) [55]
	Panulirus homarus	Subadult	Bottom dwelling animal; slow intermittent feeder	N/A	Nocturnal ; fed single dose daily (18:00 hours)	Saleela et al. (2015) [8]
	Jasus edwardsii	Adult	N/A	Lobster fed at rate 2% of their BW per day, given two feeds per week of 7% BW	Feed during daytime	Bryars & Geddes (2005) [54]
Prawn	*Penaeus monodon*	Broodstock	N/A	Fed to slight excess	10.00 and 17.00 daily	Marsden et al. (1997) [23]

*N/A: Not available

2.1. Dry pellet

Dry pellets can be used in a variety of forms; dry-sinking pellet, extruded sinking pellet, and extruded floating pellet. Suitable feed ingredient selection, together with proper manufacturing procedures such as the extrusion process ensure good water stability which is the main criteria in producing good quality feeds. The extrusion method is different from the steam pellet in that the extruder does not use any pellet binder to add adhesion to the particles [58]. Extruded pellets are more brittle where they only expand through gelatinization of starch upon cook [59]. Tuber starches such as potato and tapioca are popularly used as binding agents since they are high in amylopectin–amylose [60] and starch enzyme amylase [61] where these starches become activated and absorbs large volumes of water during the gelatinization process. Once cook, the starch containing amylose leaches from the granules which increases viscosity in the dough, aided in the thickening of feed during formulation [60]. The gelatinization of starch helps to improve feed digestibility in animals [62].

Overall, dry-sinking pellets are more practical for bottom feeders such as crustaceans, particularly prawns, lobsters, and crabs [63]. Among the necessary steps in the formulation of water-stable dry pellets included the use of good binding agents and finely ground ingredients to ensure maximum adhesion of the binder molecules. Whereas, extruded floating pellets are 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.

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 amongst aquaculture practitioners for broodstocks maturation [44]. Regardless of their acceptance in the hatcheries, no commercialization of moist feeds has occurred. Due to their high moisture content, 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 lower, and under the permissible level to avoid yeast and mold growth, with the addition of chemical agents [21].

2.2.1 Palatability and attractability

Optimization of feed intake is determined by a good physical attributes of the pellets, which includes the palatability and acceptability of the feed to animals, taking into consideration species behavior and physiological requirements as well [41]. Priority is given to ensuring that nutrition reaches the animal with minimum leaching to water. Absence of attractants or palatability features in the pellets result in declining feed consumption, hence poor growth in the crustaceans. Palatability and attractability of feeds are thus necessary which will lead to good ingestion and utilization of the prepared nutrients. Palatability is defined as the acceptance of the feed by the animals, and results in the increasing of the body weight, whereas attractability involves the animal's orientation towards the presence of any feed that has been offered [29].

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 geared towards search for food. Both features ensure higher feeding rates in the animals. Diets of low-palatability and attractability may result in crustaceans not being able to meet optimum nutritional requirements. Good palatability is determined through feed intake [65], while low food conversion ratio (FCR) as indicator of the efficiency of the feed design, or feeding strategy [66]. A good attribute in the pellet such as strong smell, or good binding factor will help the crustacean find the pellet as well as reducing the risk of nutrient loss from the pellet, due to leaching. Insufficient levels of attractants can result in low feed intake, and eventually result in poor growth of the organisms.

2.2.2 Type of binder

Aquatic feed formulation involve the use of good quality binding agents as a primary ingredient that help in stabilizing feed during exposure to water and to enhance feed floatation time [67]. Many types of binders have been used while formulating high durability pellets to increase the water stability and to minimize nutrient leaching, through added cohesion of the particles, and reduction of void spaces. Binders used include agar, starch, gelatine, carrageenan, and carboxymethylcellulose (CMC). Good binder selection with correct at 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 play an important role in the aquafeed, by providing the animals with necessary carbohydrates as well as being a binder responsible for adhesion of the feed components. Extruded pellets depend on the gelatinization in starch since no binders are typically used in the formulation. Starches such as maize, millet, guinea corn, wheat, and cassava, all improve pellet durability, contain high protein levels and make a good binder for extruded feed pellets [15]. These types of binder are capable of generating air traps in 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 [68]. Ruscoe et al. [41] compared the use of carrageenan, CMC, agar, and gelatin as the binders at different concentration in freshwater crayfish and concluded that 5% concentration of both carrageenan and CMC were significantly better than both agar and gelatin. Meanwhile, research carried out by Paolucci et al. [69] regarded agar as performing better when 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 begins once the solution cools down to gelling temperature of range 32 – 43 °C [69].

2.2.3 Water stability and durability

Compared with fish feed pellets, pellet disintegration and nutrient leaching in crustacean feed pellets requires more attention because of the nature of crustaceans as benthic-residing organisms and slow feeders [28]. Physical features such as pellet stability and durability especially are more critical than for feeds for other species where larger pellet sizes are used [41], with longer soaking time and the least possible leaching of nutrients [70]. It is suggested that crustacean pellets must maintain a minimum of 90% dry matter retention after 1 hour exposure in water, thus the use of dry pellets is unsuitable as they do not solve the nutrient leaching problems [71]. 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 food into smaller bites prior to ingestion [42]. Hence, sinking and water stable pellets are necessary.

Pellet water stability is defined as the ability of the pellet to retain both its integrity and nutrients while in water, until consumed by the animal [28]. Meanwhile, durability is defined as the ability of the pellet to maintain its shape during handling, transportation, and inflation upon transmission to water without breaking into smaller particles [59]. In aquatic pellets, the stability of pellets in water is determined by the type of binding agent that is used to hold the pellet together. Good water stability in pellets defines its effectiveness in optimizing feed intake in crustaceans during harsh handlings and vigorous mastication of the feed so that the nutrients required for growth will be effective. Species behavior factor such as slow feeding rate and external factors such as high water currents and strong aeration in the tank will all tend to accelerate pellet disintegration resulting in nutrient leaching [41, 59] and consequently increase the water clarity and turbidity from the suspended materials will be increased. The use of binders helps to hold feed components together, minimizing void spaces, maintaining pellet integrity thus producing a more compact and durable pellet [41].

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 [72]. The use of different ingredient combinations, in particular binding agent selection is responsible for pellet characteristics such as pellet buoyancy, good water stability, digestibility, minimum wastage of raw materials, and low water pollution [73]. Fish feeds typically require good binding agents that will help in stabilizing the feed and prolong feed floatation period while maintaining nutritional value. Sinking of the uneaten feed to the pond or tank bottom as a result of short floatation time will eventually cause water quality deterioration, and the high nutrient inputs might act as a fertilizer to trigger algal blooms [74]. Additional cost might be incurred while maintaining good water quality due to poor feed performance [75]. Good binding agents contribute to minimization of wastage and provide the fish with optimum nutrient utilization [67]. The use of floating feeds are advantageous as they help the farmer to closely observe feeding activity of fish, meaning that uneaten feed can be discarded immediately thus preventing low water quality problems [76].

Unlike fish, long-term sinking pellets are preferable for bottom feeders and slow eaters, and are characterized by a less expanded structure and high densities. Compared to floatation fish feeds, the sinking pellets offer longer float time which suits slow, bottom feeders such as crayfish [41], shrimp [78, 79] and mud crabs [44, 80]. For these reasons, the moist or dry sinking pellets are more appropriate for these species since the feeds are high in density compared to floating pellets. Experiments on soft shell portunid crabs observed that crabs having difficulty grasping the floating feed with their claws signified that sinking pellets would be more appropriate [80].

3. Diets

Table 3 shows macro- and micronutrients at different crustacean life stages. The main group of macronutrients in crustacean related diet studies are protein, carbohydrates, and lipids, while micronutrients include vitamins, minerals, and feed additives (Table 3). Nutrition plays an important role in the development of ovaries [1]. Some crustacean species can survive a period of starvation from insufficient food supply by using lipid reserves to sustain energy metabolic functions which this retards growth and reproduction activities in the crustacean [81]. Selection of feed in the aquaculture may determine time taken for the crustacean to reach sexual maturation. Lipids and proteins are described as the most important component of the nutrient classes, acting as the main source of nutrient for embryonic development [82].

3.1 Protein requirement for crustacean broodstock

Protein is one of macronutrients in crustacean feed ingredients that takes part in promoting growth, fattening, and reproductive processes of aquatic animals. Optimum protein levels are especially important in juvenile crustaceans since they actively grow through molting activities. Inadequate amount of protein supply hinders growth [83], sometimes causing mortalities especially in the juveniles during the prolonged intermolt period [49]. Yet, dietary protein surplus results in water deterioration from degradation of protein leftovers which form ammonia or total ammonia nitrogen (TAN) [84].

Table 3: Crustacean's macro and micronutrients

Crustacean's group	Life stage	Macronutrients						Micronutrients		Feed additives	Reference
		Protein	Carbohydrates	Lipid derivatives				Vitamin	Mineral		
				Lipid	Cholesterol	Fatty acids	Carotenoid				
Prawn	Adult	54.6%	N/A	10.7%	1.1%	ARA = 2.4% EPA= 11.2% DHA=32.9%	β-carotene 0.004; Astaxanthin 0.004	5.0%	3.0%	Lecithin	Marsden et al. (1997) [23]
Shrimp	Postlarvae	Isonitrogenous feed 21% dry weight	N/A	77.1 - 85.9%	3%	N/A	N/A	2.5%	2.0%	Soy lecithin, antifungic, antioxidant (ethoxyquin), Vitamin E	Martínez-Rocha et al. (2012) [32]
	Postlarvae	30%	42.1%	6%	0.5%	N/A	N/A	1.0%	4.7%	Lecithin, alpha cellulose, alginate, sodium hexametaphosphate	Velasco et al. (1998) [27]
	Juvenile	35%	N/A	8%	0.2%	DHA: 0.5% ARA: 0.13%	N/A	2.0%	0.5%	Calcium phosphate dibasic, lecithin, StayC	Samocha et al. (2010) [25]
	Juvenile	32.1%	48.1%	5.84%	N/A	N/A	N/A	8.53%	8.53%	Soybean lecithin, alginic acid	Gonzalez-Galaviz et al. (2020) [26]
	Juvenile	40.08 - 42.93%	33.09 - 36.4%	7.37 - 8.39%	0.1%	N/A	N/A	0.5%	0.2%	Lecithin, alginate	Suresh et al. (2011) [29]
	Juvenile	34.2% to 36.3% dry weight	40.5% to 44.3%	3.9% to 6.0% dry weight	N/A	N/A	N/A	1.8%	0.5%	Choline chloride, Stay-C 35% active	Galkanda-Arachchige et al. (2019) [38]
	Juvenile	36%	N/A	8%	0.1%	N/A	N/A	1.8%	0.5%	Choline chloride, Stay-C250 mg/kg, CaP-diebasic, lecithin, chromium oxide	Fang et al. (2016) [33]
	Juvenile	42.2%	N/A	9.1%	0.5%	N/A	N/A	2.0%	2.0%	Calcium phosphate, soya lecithin	Palma et al. (2008) [34]
	Juvenile	39.7%	30.7%	9.45%	0.16%	N/A	N/A	0.28%	0.28%	Krill meal, monocalcium phosphate, lecithin	Derby et al. (2016) [30]

	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. (2020) [37]
	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. (2019) [85]
	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. (2019) [40]
	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. (2019) [39]
	Juvenile	Isonitrogenous feed 36% crude protein	N/A	7.9 - 9.00% lipid	0.11%	N/A	N/A	0.25%	0.25%	Antioxidant, antifungic agent, Vitamin C, choline chloride,	Gamboa-Delgado et al. (2019) [31]
	Juvenile	37%	38.32 to 38.88%	10%	0.5%	N/A	1.46% (5% from 29.23% carotenoid extracted)	1.0%	1.0%	Monocalcium phosphate, cellulose	Simião et al. (2019) [56]
Crayfish	Juvenile	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	N/A	N/A	Sodium (1.4% to 1.5%), Calcium (3.3%) & Iron (0.7% to 1.3%)	N/A	Volpe et al. (2012) [42]
	Juvenile	Isonitrogenous (40% protein as-fed basis)	28.33%	7.03%	0%	ARA: 1.09% EPA: 3.58% DHA: 7.94%	N/A	2.0%	0.5%	Lecithin, dicalcium phosphate, Vitamin C, choline chloride	Thompson et al. (2003) [7]

Crab	Juvenile	44.85% to 46.73% dry matter	N/A	7% and 12% lipid	0.50%	DHA/EPA ratio between 2.2 and 1.2 when supplied with optimal n-3 LC-PUFA at 7% and 12% lipid, respectively	N/A	1.00%	1.50%	Monocalcium phosphate, choline chloride, cellulose	Wang et al. (2021) [86]
	Juvenile	Isonitrogenous with 43.64 to 46.08% dry weight	17.2 kJ g^{-1}	Dietary lipid level of 8.52% – 11.63% (op timum 9.5%)	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. (2015) [46]
	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: 14.1%; DHA: 11.7%	N/A	3.00%	2.00%	Lecithin, sodium alga acid, squid paste, cellulose	Zhao et al. (2016) [47]
	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. (2011) [44]
	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, phoshitan C, alpha-tocopheryl acetate	Alava et al. (2007) [57]
	Juvenile	46.9% to 47.03% dry weight	N/A	Isolipidic feed ~8% dry weight	0.50%	N/A	0.009% β-carotene	1.50%	5.00%	Cellulose, dextrin, lecithin	Unnikrishnan & Paulraj (2010) [49]
	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. (2010) [48]

	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 (2002) [45]
	Juvenile	Isonitrogenous 48.5%	N/A	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%	4.00%	Taurine, choline chloride, vitamin A, Vitamin D_3, Vitamin E	Sheen & Wu (1999) [50]
	Juvenile	46.6% protein dry weight	N/A	8.6% lipid dry weight	0.51%	N/A	0.01% Astaxanthin	4.00%	4.00%	Taurine, choline chloride, vitamin A, Vitamin D_3, Vitamin E	Sheen (2000) [51]
	Juvenile	44.0 - 45.7% dry weight	N/A	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%	4.00%	Taurine, choline chloride, vitamin A, Vitamin D_3, Vitamin E	Sheen & Wu (2002) [52]
Lobster	Juvenile	Isonitrogenous 53% dry weight	N/A	10.04%	2%	N/A	1% Carophyll pin (8% astaxanthin)	1.1%	0.6%	Lecithin, Stay-C	Marchese et al. (2019) [53]
	Juvenile	25% and 35% protein	23.75 - 24.73%	6.2 - 7%	N/A	N/A	N/A	5%	5%	Vitamin C, Vitamin E, Calcium carbonate, dicalcium phosphate	Perera et al. (2005) [55]
	Subadult	54.5%	17.6%	N/A	N/A	N/A	N/A	1%	1%	Casein, cod liver oil, sodium chloride di-sodium hydrogen orthophosphate and supradin powder	
	Adult	N/A	N/A	N/A	0.2%	N/A	0.15% and 0.25% Carophyll Pink	0.2%	N/A	Vitamin C, lecithin, Banox E	Bryars & Geddes (2005) [54]

*N/A: Not available

Information on species-specific dietary protein requirement is of vital importance to ensure good growth and maturation. Many investigations have been carried out to determine the protein requirement of different crustaceans such as prawns, shrimps, swimming crabs, and mud crabs. The results showed that the protein requirements are species specific, ranging from 22% to 60% [45, 49, 84] where the dietary protein intake in juvenile or early life stages of animals are usually higher in comparison with intakes of 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 [17, 87]. Lipids, along with proteins and carbohydrates share importance in providing the body with energy. Lipid differs from protein and carbohydrates in the way that it provides energy, which is twice as intensive as both proteins and carbohydrates, serves as structural component of cell membranes, and is an important signaling molecules [88]. Neutral lipids, particularly triacylglycerols or triglycerides are the principal form of energy source found in the adult, egg, and larvae of most crustaceans [57]. Phospholipids primarily functions in the building of the cell membrane [89]. Cholesterol is the best known sterols that serves as a precursor of physiological components including sex hormones, particularly ecdysone that regulates molting activities in crustaceans [51, 90]. Feeds containing dietary cholesterols are essential to ensure good growth and survival in crustaceans. Fatty acids govern a wide range of physiological processes including reproductive performance and egg quality in crustaceans [82].

Studies demonstrated that lipid levels in most crustaceans increase with size with adults having higher lipids levels than the juveniles. Some reserved lipids are catabolized as energy sources, while others are stored in the gonad for structural purposes, such as maturation and eicosanoid synthesis [90]. The information on lipid requirements is very important in the development of formulated feeds to ensure the nutrients suffice for good growth and maturation [17, 87]. Previous studies have shown that the determination of lipid requirements is generally species specific, and are different for different developmental stages. Nevertheless, collective prior studies on crustaceans have concluded that optimum growth can be achieved with a total lipid level from 2% to 10% [47] or from 2% to 12% of diet dry weight [45].

The fatty acids can be 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 with a single double bond in their carbon chain. Unlike SAFA and MUFA, polyunsaturated fatty acids (PUFA) contain more than one double bond in their carbon backbone. They act as precursors for animal hormones and play an important role in regulation of cell membranes. PUFA are commonly generated from plant synthesis as plants are the primary producers of carbon in marine ecosystems, including synthesis of various important biological molecules such as carbohydrates, proteins, and lipids [91]. 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 these [92].

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 and reproductive rates and for high food conversion rates in both marine and freshwater organisms [93]. 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; $C \geq 20$). The consumption of diets containing EPA and DHA helps to optimize animal growth [92] while ARA functions as the precursor for eicosanoids which regulate reproductive success and sexual behavior of females [94]. In general, EPA and DHA can be obtained from the consumption of plant materials or through a 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 [96, 97].

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, but the attractants that enhance palatability as well as the inclusion of the correct proportion of nutrients to boost animal performance. Knowledge on the possible interactions between food, feeding and diets in crustaceans needs to be updated and improved to increase the quality of seed or broodstock produced in captivity, especially in commercial aquaculture. The studies performed so far have demonstrated a clear interaction between food types, feeding behavior, and diets, especially for the crustacean group, with reference to the graphical explanation in the graphical abstract.

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

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