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Developing sustainable, cost-effective and high-performance shrimp feed formulations containing low fish meal levels

Alberto J.P. Nunes[a], Lise Lotte Dalen[b], Geronimo Leonardi[b], Lena Burri[b,*,1]

[a] LABOMAR - Instituto de Ciências do Mar, Universidade Federal do Ceará, Avenida da Abolição, 3207 - Meireles, Fortaleza, Ceará 60.165-081, Brazil
[b] Aker BioMarine Antarctic AS, Oksenøyveien 10, 1366 Lysaker, Norway

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ABSTRACT

Feed formulations for marine shrimp have adapted to the stagnant fish meal supplies and increasing prices by progressively moving to alternative protein sources such as plant and rendered animal by-products. This review presents the current challenges on the use of conventional and non-conventional feed sources, with a focus on solving the economical, sustainability and performance challenges of low-fish meal diets. As a case study, this review shows that krill meal can be included to address some of these concerns, such as missing essential nutrients, lower attractability/palatability and antinutritional factors that suppress feeding stimulus, reduce nutrient bioavailability and hence increase production costs. The combination of protein, nutrients and feed attractants of krill meal is useful to address the disadvantages of alternative feed ingredients which range from being poorer feeding effectors to having lower bioavailability of nutrients. It can therefore be used as a formulation tool to decrease the reliance on fish meal, which opens the way for alternative ingredients that improve the cost efficiency and sustainability of feeds.

1. Introduction

Commercially-farmed marine shrimp is a highly valued aquatic protein source ranked among the most-consumed seafood worldwide (https://www.fao.org/documents/card/en/c/ca9229en/). In 2018, exports of shrimp were valued at USD 25.7 billion, accounting for almost 16 % of all internationally-traded value among fishery products (Anon, 2021). Aquaculture has had a major contribution to the globalization and commoditization of seafood driving the increase in per capita world consumption (Anderson et al., 2018). Production of shrimp in captivity alone has increased by more than 10-fold over the past 30 years, from 619.4 thousand mt in 1989–6.5 million mt in 2019 (Anon, 2022). Since wild stocks are small or declining, the contribution of aquaculture to the world shrimp supply now accounts for more than 83.7 %.

Modern shrimp aquaculture is dependent on the provision of industrially manufactured compounded feeds to sustain its consistent rate of expansion in production. Practical shrimp feeds contain crude protein (CP) levels ranging between 25 % and 40% (on a fed basis) higher than those used for farmed land animals (poultry, swine and livestock) (Amaya et al., 2007; Nunes et al., 2014). Feed mills need to rely on continuous and constant availability of high protein ingredients obtained mainly from capture fisheries, agriculture and animal rendering. Historically, fish meal has been the protein of choice due to its high bioavailability of nutrients and ability to stimulate feeding activity in marine shrimp (Nunes et al., 2014). However, world supply of fish meal made from wild-captured forage fish is at stake, with limited or no prospects of increase in production in the future (FAO, 2020; Jannathulla et al., 2019). As a result, there is a growing move in the industry in the strategic and segmented use of fish meal in accordance to production stage (i.e., broodstock, larval, starter, and grower feeds) and intensification level. This is forcing feed mills to rely more on cheaper and more widely and locally available feed ingredients. In general, these carry a lower biological value per kg of product, have poorer attractability, and greater fluctuation in quality compared to fish meal. In order to cope with this situation, feed formulation has shifted from ingredient to nutrient basis, taking advantage of several nutritious (i.e., amino acids, vitamins, minerals, and fatty acids) and functional (i.e., palatability, digestibility, immune and gut health enhancers) feed additives that are now widely available (Nunes et al., 2014; Encarnação, 2016; Hoseinifar et al., 2017). Additives can fill the gaps in formulation to fully

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[*] Corresponding author.

E-mail addresses: alberto.nunes@ufc.br (A.J.P. Nunes), lldalen@hotmail.com (L.L. Dalen), geronimo.leonardi@akerbiomarine.com (G. Leonardi), lena.burri@akerbiomarine.com (L. Burri).

[1] https://orcid.org/0000-0002-0099-504X

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satisfy shrimp nutrient requirements, while enhancing physiological responses, including feeding stimulation, digestion, and resistance to environmental stress and diseases (Encarnação, 2016). The dietary supplementation with the so-called "feeding effectors" has become a precondition when challenging dietary fish meal levels (Soares et al., 2021). Feeding effectors are compounds that have the ability to attract shrimp to a food source and stimulate feeding (Soares et al., 2021). Attractants are categorized as those compounds that lead to the first phases of feeding responses in shrimp, which include detection, orientation and locomotion towards the food source (Nunes et al., 2006). Compounds that act as feeding incitants and stimulants promote initiation and continuation of feeding (Mendoza et al., 1997). The terms attractants and feeding incitants/stimulants are collectively called feeding effectors.

Most of the feeding effectors identified for marine shrimp are found in protein-rich ingredients of marine origin including fish meal, fish solubles, fish hydrolysate, squid head offal meal, squid liver meal, shrimp head offal meal, krill meal, krill hydrolysate, and bivalve meals from clams, oysters and mussels (Nunes et al., 2006; Grey et al., 2009; Smith et al., 2005; Guillaume et al., 1989; Suarez et al., 1985; Cruz-Ricque et al., 1987; Suresh and Nates, 2011; Derby et al., 2016). Incorporation of these ingredients and/or compounds into shrimp diets have long been used to enhance shrimp feeding responses at levels ranging from 0.5 up to 5% of the diet (as-is basis) (Hartati and Briggs, 1993). Although shrimp have a rudimentary vision, they are equipped with chemosensory structures able to detect and identify chemical signals in water and discriminate food in regards to their palatability (Bardera et al., 2019). As an example of such a feeding effector, this review discusses the use of low inclusions of krill meal toward developing sustainable, cost-effective, and high-performance shrimp feed formulations.

2. Shrimp farming systems and their dependence on feed inputs

Shrimp form a large group, comprised of approximately 2500 species (Farfante, 1988). However, only 343 species are commercially important (Holthuis, 1980). It is in the Penaeidae family, that the two most important commercially-farmed species, the Pacific whiteleg shrimp, *Litopenaeus vannamei* and the tiger shrimp, *Penaeus monodon* are found. According to FAO (https://www.fao.org/documents/card/en/c/ca9229en/) these two species accounted for 52.9 % and 8.0 %, respectively, of the global crustacean farmed production in 2018 estimated at 9.4 million mt.

Marine shrimp farming worldwide occurs under different levels of intensification, in extensive, semi-intensive, intensive, or super-intensive culture systems (Table 1). Variations exist within each production system, in terms of design, engineering, operation, and management, but their level of intensification is clearly distinguished by their dependence on the external supply of dissolved oxygen (DO) and source of nutrients available for shrimp growth.

Extensive culture was historically the first to emerge (Chinabut and Puttinaowarat, 2005). This system operates by promoting the development of natural pond productivity through water fertilization. Shrimp will graze on a variety of naturally occurring food sources, including detritus, plant material and animal prey. These food sources compromise all of the shrimp's diet and the only source of nutrients to their growth. As a result, this system is characterized by low stocking densities (i.e., 1–3 shrimp/m^2) and yields that seldom exceed 0.3 mt/ha/crop. Semi-intensive ponds are an evolution of extensive culture practices and are considered more efficient and sophisticated. Earthen ponds occupy large areas between 5 and 20 ha and depths from 0.7 to 1.2 m. The shrimp's natural diet, which develops in the pond, is supplemented with inputs of compounded feeds that may contain between 25 % and 35 % CP (as-fed basis). Such characteristics and procedures enable higher stocking densities (i.e., 8–25 shrimp/m2) and yields of 0.8–2.5 mt/ha/crop. Under this level of intensification, feeds are formulated to contain essential nutrients at quantities slightly below the optimal levels required by shrimp. However, feeds are designed to be consumed and digested efficiently, supplying a cost-effective nutrition in balance with the availability of natural food to maximize growth performance. In both extensive and semi-intensive systems, the dynamics of DO concentrations are dominated by respiration and photosynthesis. However, mechanical aeration may be adopted in the latter as an emergency tool or to control night-time DO concentrations.

Intensive shrimp farms can either be designed and built to operate under this condition or be adapted from semi-intensive systems. Intensification is often carried by reducing pond size (1–5 ha), increasing pond depth (1.2–1.5 m) and installing electricity throughout the farm area to support mechanical aeration systems (4–12 hp/ha). Stocking densities range between 40 and 70 shrimp/m2, so both water exchange and paddle-wheel aeration are applied to provide minimum levels of 3 mg/L of DO. Natural pond food is scarce, therefore complete feeds with 35–38% CP are used to support yields between 3 and 8 mt/ha/crop.

Super-intensive shrimp farming is carried out in square, rectangular, and circular ponds or tanks with areas between 2500 and 4000 m2, and depths between 1.8 and 3.0 m. Ponds are lined with high density polyethylene geomembranes or made with concrete. The system often operates with central drains, commonly known as "toilets" to flush out organic matter. There may be basins for water reuse, in addition to greenhouse cover to increase and control water temperature. DO concentrations are kept above 5 mg/L through 24-h aeration often, but not necessarily, using a combination of diffused aeration tubing rested near the pond bottom with paddle-wheel aerators arranged diagonally or in parallel to the pond walls. This is intended to eliminate stagnant pond

Table 1
Characterization of commercial production systems used in *L. vannamei* culture.

Operational parameters	Shrimp production systems			
	Extensive	Semi-Intensive	Intensive	Super-Intensive
Pond type, shape	Earthen, irregular	Earthen, irregular	Earthen, rectangular	Lined or concrete, rectangular, square
Pond area (ha)	> 20	5–20	1–5	0.25–0.4
Pond depth (m)	0.5–1	0.7–1.2	1.2–1.5	1.8–3.0
Stocking density (shrimp/m^2)	1–5	8–25	40–70	120–300
Source of dissolved oxygen	Photosynthesis	Photosynthesis, water exchange, and paddle-wheel aeration (emergency or night-time, <4 hp/ha)	Photosynthesis, water exchange, and paddle-wheel aeration (night-time, 4–12 hp/ha)	24-h, paddle-wheel aeration (surface) and/or diffused aeration tubing (bottom)
Source of nutrients for shrimp growth	Natural pond food organisms	Natural pond food organisms and supplemental feed	Complete feeds	Complete feeds
Feed	None	25–35% crude protein, partially complete in all nutrients	35–38%, complete in all nutrients	35–38%, complete in all nutrients
Final shrimp yield (mt/ha/crop)	0.3	0.8–2.5	3–8	Up to 25

areas and to assist with sludge control, by creating a circular water pattern around the center of the pond. In this system, stocking densities can range from 120 and 300 shrimp/m2 with yields that can reach 25 mt/ha/crop. Similar to intensive production, feeds are nutrient-dense and complete in all nutrients.

3. Feed formulation

3.1. Nutrient levels adapted to species and culture system

Three basic pillars define the nutrient profile of formulated shrimp feeds: the farmed shrimp species, its growth stage and nutrient requirements, and the culture system or level of intensification adopted (Nunes et al., 2014). Most nutrition studies published on the quantitative requirements of the essential nutrients for penaeid shrimp have focused on four major species, the Kuruma shrimp (*Marsupenaeus japonicus*), the oriental shrimp (*Fenneropenaeus chinensis*), *P. monodon* and *L. vannamei*. The National Research Council (Anon, 2011) has made recommendations for the minimum levels of 45 essential nutrients in shrimp feeds (Table 2). However, despite being ranked as the most farmed-shrimp species worldwide, the requirements of several key nutrients for the whiteleg shrimp have not yet been fully determined. As this species has lower requirements for essential amino acids (EAAs) when compared to the tiger shrimp, for example, it is likely that the quantitative requirements of other essential nutrients respond the same (Anon, 2011).

When formulating based on the published nutrient requirements, one needs to consider that most nutritional studies are carried out under controlled conditions, often using clear-water, small tanks or aquariums, low number of animals, and post-larval or early-stage juvenile animals. Shrimp are also fed diets containing purified or semi-purified ingredients (casein, formulated in excess or to match all the species' nutrient requirements, except the nutrient under investigation. For example, when studying the requirement of methionine, casein can be used as the main protein source. The diet is also supplemented with an amino acid mixture containing both essential and non-essential sources of crystalline AAs. Since crystalline AAs are prone to leach in water, they are often supplemented 10 % above the animal requirements. These conditions significantly deviate from an industrial setting, where shrimp are raised with compounded feeds made from raw materials that may contain anti-nutritional factors that negatively affect the digestibility and absorption of nutrients (Nunes et al., 2014). In addition, under less intensive culture environments (e.g., semi-intensive ponds) there can be a significant contribution of endogenous food sources to the farmed animal's nutrition and growth (Gamboa-Delgado, 2014). Thus, in the presence of natural productivity, nutrient thresholds below shrimp requirements are implemented (e.g., 10 % or more depending on shrimp growth stage, availability of natural food, desirable feed performance and production targets). This approach is often adopted when formulating feeds for semi-intensive culture systems where naturally available food items serve as a reliable source of essential nutrients for the farmed animal's nutrition (Table 3).

In feed mills, formulators work with a least-cost formulation software to match the targeted levels of essential nutrients with the lowest economical cost possible (Pastore et al., 2012; Suresh, 2016). Nutrient levels are mostly met by combining a range of raw materials that contain energy and intact nutrients such as proteins, amino acids, lipids, fatty

Table 3
Contribution of exogenous food sources to the growth of marine shrimp under different levels of intensification. Contribution was estimated by the analysis of shrimp stomach content or through stable carbon isotope analysis of shrimp tissues.

Species	Stocking density (shrimp/ m^2)	Body weight (g)	Natural food contribution (%)		Authors
			Stomach	δ^{13}C	
Farfantepenaeus subtilis	10	1.6 – 14.6	75.1	84.4	(Nunes et al., 1997)
Litopenaeus stylirostris	200	0.24 – 1.18	–	36.9	(Cardona et al., 2015)
Litopenaeus vannamei	9 – 15	1.9 – 11.9	80 – 97	–	(Gamboa-delgado et al., 2003)
	20	1.5 g – 12	–	53 – 77	(Anderson et al., 1987)
	128	3.04 – 14.82	–	< 1 – 20.3	(Castro et al., 2021)
Penaeus monodon	4	0.8 g – 15.35	100	–	(Bombeo-Tuburan et al., 1993)
	7	0.35 g – 17.6	63.7	–	(Focken et al., 1998)
	8	PL – 22	79	–	(Moorthy and Altaff, 2002)
Marsupenaeus japonicus	10	PL22 – 22	37 – 43	–	(Reymond and Lagardère, 1990)

Table 2
Essential nutrients and their recommended levels (% or mg/kg of the diet, dry matter basis) in diets for *L. vannamei*. Nutrient values were partly compiled with permission from the National Research Council (Anon, 2011). In the absence of the requirement values determined for *L. vannamei*, industry standards or recommendations for *P. monodon* and *M. japonicus* were used. Recommended digestible energy = 12.56 MJ/kg.

Protein[a]	Levels	Lipid[b]	Levels	Minerals[c]	Levels	Vitamins[d]	Levels
Dig. Protein	30 %	Total lipids	5–7.5 %	Ca	1.0 %	A	1.4 mg/kg
Arg	1.6–1.9 %	LNA	0.9–1.1 %	Cl	–	D3	100 μg/kg
His	0.6–0.8 %	LOA	0.7–1.2 %	Mg	0.15 %	E	100 mg/kg
Iso	1.0–1.3 %	EPA	0.25 %	Avai. P	0.35 %	K	35 mg/kg
Leu	1.7–1.9 %	DHA	0.25 %	K	1.2 %	B1	14 mg/kg
Lys	1.6–2.1 %	Cholesterol	0.13–0.15 %	Na	0.35 %	B2	23 mg/kg
Met	0.7 %	PL	1.2–1.5 %	Cu	16–32 mg/kg	B6	80–100 mg/kg
Met+Cys	1.0 %			I	–	B5	100 mg/kg
Phe	1.4–1.5 %			Fe	< 12 mg/kg	Niacin	7.2 mg/kg
Thr	1.3–1.4 %			Mn	24–32 mg/kg	Biotin	2 mg/kg
Trp	0.2–0.4 %			Se	0.2–0.4 mg/kg	B12	0.2 mg/kg
Val	1.4 %			Zn	15 mg/kg	Folic acid	2 mg/kg
						Choline	600 mg/kg
						C	350 mg/kg

[a] Dig. protein, digestible protein; Arg, arginine; His, histidine; Iso, isoleucine; Leu, leucine; Lys, lysine; Met, methionine; Met+Cys, methionine plus cysteine; Phe, phenylalanine; Thr, threonine; Trp, tryptophan; Val, valine

[b] LNA, linolenic acid; LOA, linoleic acid; EPA, eicosapentaenoic acid; DHA, docosahexaenoic acid; PL, Phospholipids

[c] Ca, calcium; Cl, chlorine; Mg, magnesium; Avail. P, available phosphorus; K, potassium; Na, sodium; Cu, copper; I, iodine; Fe, iron; Mn, manganese; Se, selenium; Zn, zinc.

[d] A, retinol; D3, cholecalciferol; E, tocopherol; K, phylloquinone; B1, thiamine; B2, riboflavin; B6, pyridoxine; B5, pantothenic acid; B12, cobalamin; C, ascorbic acid

acids, and carbohydrates. When nutrient levels are unachievable, unbalanced and (or) economical costs are high, the software will supplement the feed recipe with available additives (i.e., vitamins, minerals and crystalline AAs). This makes the formula more cost-effective while moving away from a formulation approach dependent solely on raw materials (Nunes et al., 2014). The bulk of the final cost of a finished feed is the balance between pre-specified dietary nutrient levels, ingredient prices, and feed manufacturing practices.

3.2. The main cost drivers in feed formulation

It is widely known that feed represents the main cost element in the production of farm-reared shrimp. In a feed mill, raw materials represent more than 50 % of the total manufacturing costs of a commercial shrimp feed. The other expenses are associated with manufacturing, packaging, distribution, general and administrative expenses, marketing, research, and development.

As an example, a typical grower marine shrimp feed recipe for the semi-intensive culture of *L. vannamei* may consist of 36 % soybean meal, 12 % fish meal, 5 % poultry meal, 3 % squid meal, and 1.4 % corn gluten meal (% of the diet, as-fed basis; Table 4). These feed materials are mainly used to meet a minimum level of CP that is generally around 35 % for grower feeds. In addition, 27 % wheat flour is added to the formula along with 6 % broken rice as sources of digestible energy and starch to ensure an adequate physical water stability. Shrimp formulas do not contain much oil, usually between 1 % and 3 % fish oil used to supply digestible energy and the needed omega-3 polyunsaturated fatty acids (n-3 PUFAs). Soy lecithin is included as the main source of phospholipids. Therefore, based on this example, it is possible to verify that most of the formula, 57.41 %, is comprised of protein raw materials and crystalline amino acids (CAAs) which correspond to more than 2/3 of the total formula cost. Since protein and AAs are by far the most expensive class of nutrients in shrimp feeds, attempts to reduce formulation costs have focused on optimizing their use through more precise nutrient levels aligned with culture conditions and (or) reducing the reliance on expensive protein sources, such as fish meal.

4. Protein sources in shrimp feeds

4.1. Marine proteins

Fish meal has historically represented the main marine protein source used in shrimp feeds (Tacon and Metian, 2008). The bulk of fish meal used in aquaculture feeds is still supplied by capture fisheries. This type of fish meal is made from small forage fish, such as anchovy, menhaden, mackerel, capelin, sardine, and herring (Bórquez and Hernández, 2009; Venkateswarlu, 2019). These are small species of fish that occupy a low trophic level in the sea, and feed through water filtration using their gill rakers to retain planktonic-sized organisms (Ben-Tuvia, 1995). Despite their high energy and nutrient value in terms of protein, EAAs, n-3 PUFAs, vitamins, and minerals, there is little demand for human consumption (Jannathulla et al., 2019). Fréon et al. (2014) estimated that only 2 % of the total catch of anchovy in Peru was used as canned, frozen or cured food products with the remainder converted into feed ingredients. Therefore, these pelagic fish are captured with the goal of reducing them into feed ingredients for aquatic and terrestrial farmed animals which carries a higher price tag and a greater market demand. The industrial conversion of these pelagic fish yields 22.5 % fish meal and between 4 % and 5 % fish oil (Shepherd and Jackson, 2013). Production of fish meal have fluctuated between 6 and 7 million mt since 1990 with a forecast of only a 1 % increase in pro-duction by 2030 (). In comparison, global aquaculture production has reached 82.1 million mt in 2018, equivalent to a 527 % increase compared to the production harvested in 1990.

Climate change has also negatively influenced capture fisheries production and together with the increasing demand, the price for fish meal and oil has surged (Jannathulla et al., 2019; Barange and Perry, 2009). In 2001, the price for fish meal was 608 USD/mt and by 2021 it had increased to 1472 USD/mt (Bank, 2022). Furthermore, the prices for fish meal today are highly volatile and continue to deviate from other protein sources, such as soybean (Fig. 1). Annual mean prices of fish meal in the 1980ś were on average 55 % higher than soybean meal, increasing to 93 % in the 1990 ś, 153 % in 2000 ś and 233 % in 2010 ś. The recent SARS-CoV-2 pandemic has also demonstrated the fish meal industries' lack of resilience to shocks in the market, making the use of fish meal in feed less reliable (EUMOFA, M.Aa.F., Fishmeal and fish oil.

Table 4
Dietary inclusion (% of the diet, as-is) and relative cost contribution (%) of macro and micro ingredients and their main targeted nutrients in a practical grower shrimp feed with 35% CP.

Ingredient	Dietary inclusion (%, as-is)/Class of nutrient				
	Proteins and amino acids	Carbohydrates and starch	Minerals and vitamins	Fatty acids, phospholipids, energy	Non-nutrient
Soybean meal	36.00	–	–	–	–
Wheat flour	–	27.00	–	–	–
Sardine meal	12.00	–	–	–	–
Rice, broken	–	6.00	–	–	–
Poultry meal	5.00	–	–	–	–
Squid meal	3.00	–	–	–	–
Fish oil	–	–	–	2.13	–
Monosodium phosphate	–	–	1.51	–	–
Corn gluten meal	1.41	–	–	–	–
Soy lecithin oil	–	–	–	1.22	–
Magnesium sulfate	–	–	0.86	–	–
Calcium carbonate	–	–	0.82	–	–
Potassium chloride	–	–	0.76	–	–
Salt	–	–	0.66	–	–
Synthetic binder	–	–	–	–	0.50
Choline chlorine	–	–	0.38	–	–
Vitamin-mineral premix	–	–	0.30	–	–
L-Lysine	0.24	–	–	–	–
L-Threonine	0.13	–	–	–	–
DL-Methionine	0.07	–	–	–	–
Vitamin C	0.01	–	–	–	–
Sum	57.86	33.00	5.29	3.35	0.50
Relative cost (%)	69.6	15.3	5.99	7.67	1.44

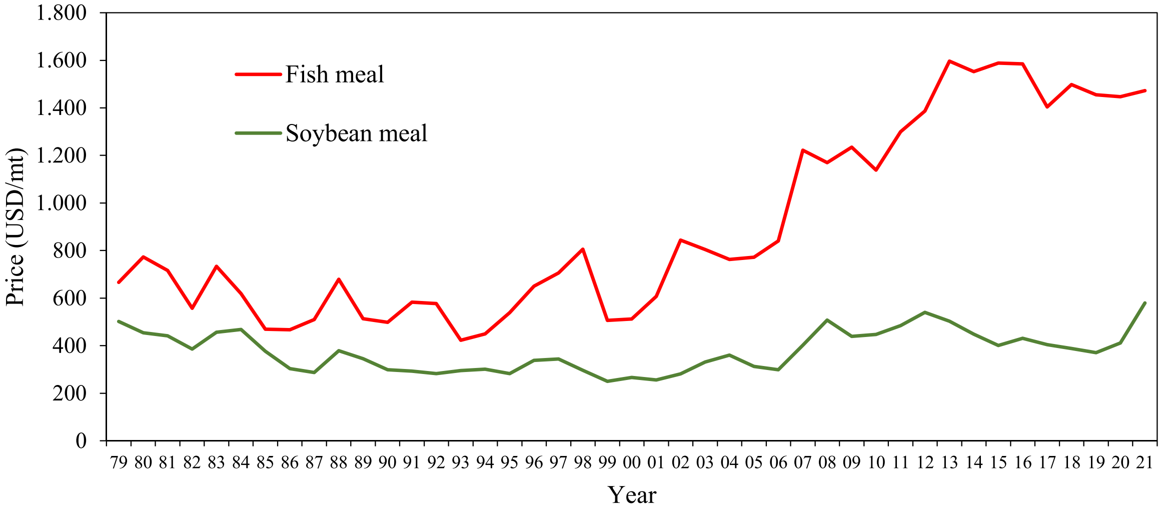


Fig. 1. Annual prices of fish meal and soybean meal between 1979 and 2021 obtained from World Bank Commodity Price Data with permission to reproduce (Bank, 2022).

Data Source: Fishmeal, from January 2021, German Fishmeal, Danish 64 % Pro, FOB Bremen; January 1999 to December 2020, German, 64 % protein, EXW Hamburg. Soybean meal, from January 2021, Soybean Pellets 48 % Pro, Brazil, CIF Rotterdam; January 1999 to December 2020, Brazilian pellets 48 % protein, CIF Rotterdam; during 1990–1998, 45/46 % c.i.f. Rotterdam, nearest forward; previously US origin 44 %.

2021: Luxembourg.).

Other marine proteins used in shrimp feeds are derived from squid, mollusks, krill, and other crustaceans, which are commercially available in the form of meals, solubles and hydrolysates. They are rich in low molecular weight compounds capable of eliciting shrimp feeding responses which significantly enhance feed attractability and palatability (Suresh and Nates, 2011). This ultimately leads to longer and increased feed consumption which becomes particularly relevant in fish meal-challenged feeds (Suresh and Nates, 2011; Derby et al., 2016). These marine proteins are included at low dietary levels, between 0.5% and 5% (as-is basis), sufficient to prompt positive feeding behavioral responses in shrimp depending on attractant type and diet composition (Nunes et al., 2006). Although these marine ingredients are not used to meet shrimp nutrient requirements as they carry higher market prices compared to fish meal, they are rich in digestible protein, AAs, n-3 PUFAs, phospholipids, cholesterol, and a number of other key nutrients. As such, they also provide some level of nutrient contribution to shrimp feed formulas which counterbalance their impact on formulation costs.

4.2. *Terrestrial proteins*

The most common practice to reduce fish meal usage has been to rely on terrestrial plant protein by-products derived from agriculture, such as meals made from soybean, canola, corn and wheat. A typical soybean meal contains between 44 % and 48 % CP and can comprise from 30 % to 40 % of the composition of a grower feed for the whiteleg shrimp. Levels in excess of 50 % have also been successfully evaluated under semi-intensive shrimp culture conditions (Roy et al., 2009; Sookying et al., 2013; Sookying and Davis, 2012). However, high soybean meal feeds are associated with antinutritional effects of oligosaccharides and trypsin inhibitors (Gatlin et al., 2007) and increased costs of re-placement wear parts of manufacturing equipment. Grower shrimp feeds have a lower requirement for high protein ingredients compared to salmon feeds (Lall, 1758; Ayisi et al., 2017). The sum of dietary CP and lipid content are not greater than 45 % in a shrimp formula providing sufficient space for use of lower CP-content ingredients. Plant protein concentrates with 60 % CP content or higher may also be included, but at lower inclusions (less than 5 %) due to their higher market prices.

Feed mills have also relied on proteins supplied by rendering facilities, which convert inedible animal by-products obtained from the slaughtering or processing of poultry, swine, and cattle into meals. Meals of meat and bone, meat, poultry, hydrolyzed feather, and blood, are the primary products resulting from the rendering processes (Meeker, 2009). The major drawback on relying on standard animal by-products as a major protein source in shrimp feeds is related to their lower bioavailability of nutrients (de Carvalho et al., 2016; Glencross et al., 2018; Lemos et al., 2009; Vieira et al., 2022) and lack of eicosapentaenoic acid (EPA, 20:5n-3) and docosahexaenoic acid (DHA, 22:6n-3), which are essential fatty acids for marine shrimp. Besides, terrestrial proteins are also considered to be poor feeding effectors (Nunes et al., 2006; Suresh and Nates, 2011).

On the other hand, the advantages of using these alternate raw materials in shrimp feeds include their greater availability and accessible prices compared to fish meal. They are also culturable and renewable, but some argue that the continuous and expanding dependence on terrestrial feed materials might pose environmental threats such as increasing the demand for freshwater, land, and phosphorus (Malcorps et al., 2019). This creates the need for feed proteins from unconventional sources.

4.3. *Unconventional proteins*

A number of insect meals have shown promising results as a protein source in shrimp feeds, e.g., black soldier fly larvae, *Hermetia illucens*, yellow mealworm, *Tenebrio molitor*, and black cricket, *Gryllus bimaculatus*, among others (Cummins et al., 2017; Motte et al., 2019; Peh et al., 2021; Shin and Lee, 2021; Sogari et al., 2019). Insect meals represent a potential sustainable source of raw material with a high nutritional value, but with a less clear level of consumer acceptance (Sogari et al., 2019; Rumpold and Langen, 2020). Bioflocs, which are mixtures of diatoms, microalgae, bacteria, and food and fecal remains, can be included into shrimp diets to reduce feed cost (Khatoon et al., 2016). Yet, bioflocs still have some challenges relating to operating costs and constant fluctuations in nutrient value (El-Sayed, 2021). Yeast is an example of single cell proteins as an alternative protein source with promising findings relating to being an effective immunostimulant (Ernesto Ceseña et al., 2021; Thanardkit et al., 2002). On the other hand, Qiu and Davis (Qiu and Davis, 2017) has shown that yeast can negatively affect growth when incorporated at a high level in shrimp feeds.

4.4. Other issues to consider with fish meal and other feed proteins

There are several factors relating to consumer demands to take into consideration when choosing a feed composition. Some feeds are based on waste from meat production, which can result in consumer aversion in countries where consumption of certain types of meat are religiously or culturally controlled or prohibited (Fieldhouse, 2017). Waste from meat production also carries the risk of pathogen transfer, such as transmissible spongiform encephalopathy (TSE), or spread of antibiotic-resistant bacteria (Haapapuro et al., 1997). Member countries of the European community, for example, have established a number of rules into the use of animal by-products for the safety of the feed chain. These include product traceability, registration and approval of rendering facilities, allowable animals and animal parts, hygiene, manufacturing, storage and disposable requirements. In the United States in 2007, 91 % of all soybean planted was genetically modified (GM) (Bonny, 2008). Whereas the use of GM soybean may negatively impact consumer perception and be affected by regulations in some countries (Bruetschy, 2019; Scott et al., 2016).

Also, the environmental impact of consumer goods is having an increasingly stronger impression on consumer choice and has enhanced the demand for more transparency of the production process. Since fish meal is becoming a further volatile resource not only in price, but also in quality and quantity, the use of plant-based feed alternatives such as soybean is promoted. Unfortunately, this comes with a significantly larger carbon footprint than fish meal and relates to other environmental problems such as water use, deforestation, biodiversity loss and eutrophication (Powers, 2005; Song et al., 2021; Burton and Miranda, 2013; Pereira et al., 2020).

Moreover, Thiele et al. (2021) found that species used for fish meal often contain microplastics (0.72 microplastics/individual (MP/i)), which are a potential threat to marine wildlife as they have detrimental physical effects (Wright et al., 2013). Further, they may have implications for human food security, as seafood ingested by humans can contain microplastics which may carry harmful microbes or toxic compounds (Barboza et al., 2018; Keswani et al., 2016). In small pelagic fish species in South Africa, Bakir et al. (2020) found that anchovy (*Engraulis encrasicolus*) contained 1.13 MP/i, herring (*Etrumeus whiteheadi*) 1.38 MP/i, and sardines (*Sardinops sagax*) 1.58 MP/i. Microplastics occurred in 57–72 % of individuals. Microplastics are also found in species whose trimmings are often used in shrimp feed (salmon 66.5 MP/kg and tilapia 18.1 MP/kg) (Gündoğdu et al., 2021). On the other hand, it has been reported that Antarctic krill meal does not contain microplastics, which may be due to lower concentrations of microplastics in their habitats, and that the microplastic does not accumulate in krill (Gündoğdu et al., 2021; Dawson et al., 2018; Isobe et al., 2017).

4.5. Certifications ensuring sustainable practices

There has been an increased interest in the market for aquaculture to show responsible behaviors, environmentally, socially, and economically (Shepherd and Jackson, 2013; Boyd et al., 2020). There are several existing certifications and initiatives to address the negative environmental impacts resulting from capture fisheries and aquaculture (Fig. 2), as well as the development of new ones (Dusík and Bond, 2022; Gephart et al., 2021).

Multiple certifications exist to ensure that the production and use of ingredients in feed are sustainable. Marine Stewardship Council (MSC) is a certification given to fisheries that manage the stocks in a sustainable way and are using a fishing method with a minimal impact on vulnerable habitats (Hønneland, 2020). To become MSC-certified, the fisheries need to meet the MSC standards and be verified by an independent accredited certification body. The fisheries also need to be well managed, making them able to adhere to relevant laws and changing environments (Hønneland, 2020). Certifications from MSC are recognized by Marin Trust Standard, and these certifications ensure a sustainable production of raw material in feed through requiring the documentation of traceability (Oloruntuyi et al., 2019). The Marine Trust Standard ensures that illegal fishing material is not used and that the raw material comes from responsibly managed fisheries. The aquaculture stewardship council (ASC) contributes to sustainable aquaculture by being an independent non-profit organization (Sherry and Koester, 2020). ASC-certified shrimp farms must meet requirements regarding biodiversity, pollution, antibiotics and social challenges (Roebuck and Wristen, 2018.). Another organization working to improve fisheries management is Sustainable Fisheries Partnership (SFP) (Veiga et al., 2016). SFP awards ratings based on the current state of the management strategy, managers' and fishers' compliance, stock health, and biomass development.

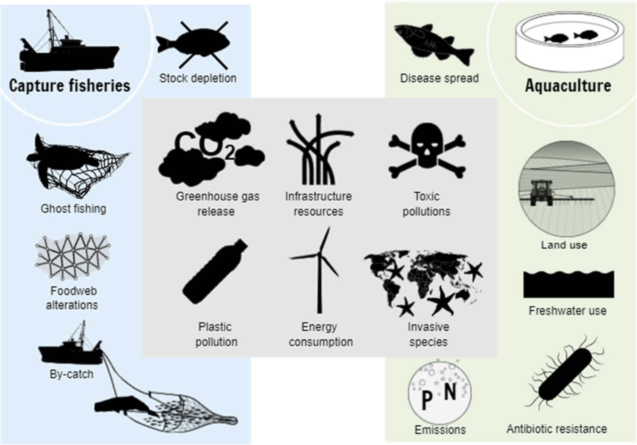


Fig. 2. Overview of potential impacts from capture fisheries and aquaculture Adapted from (Gephart et al., 2021) with permission to use from Jessica A. Gephart, Environmental performance of blue foods; published by Springer Nature, 2021.

Krill fisheries are an example of an SFP-certified fishery (Veiga et al., 2016). The Antarctic krill is caught in Area 48 off the Antarctic peninsula and the catch is limited to 1 % of the total estimated biomass in that area, ensuring no stock or species depletion, and major steps have been taken to eliminate by-catch (Krafft et al., 2021; Meyer et al., 2020). An example is the "marine mammal exclusion device", which has a fine mesh-excluder on the entrance of the net that ensures no bycatch of larger animals (Lyle et al., 2016). Technology development has made krill fisheries more energy efficient, using less or alternative fuel, reducing greenhouse gas (GHG) emissions and freshwater use, and having a higher catch rate (Meyer et al., 2020; Parker and Tyedmers, 2012).

Since 2010, the annual catch rate of Antarctic krill has steadily increased, reaching a total catch of almost 400,000 mt in 2019 (Meyer et al., 2020). Still, the total biomass has increased from 60.3 million mt in 2000–62.6 million in 2018/19 (Kaur et al., 2022; Krafft et al).

In addition to a market pull and regulatory pushes in the industry to promote more sustainable practices, the EU commission involvement in leading EU towards net zero emissions has led to the implementation of the EU taxonomy. The taxonomy is a financial instrument designed to push companies to more sustainable activities, as well as prevent "green washing" (Dusík and Bond, 2022), meaning to communicate positive environmental performance while performing poorly (de Freitas Netto et al., 2020). The EU taxonomy proposes six environmental objectives: 1) climate change mitigation; 2) climate change adaptation; 3) the sustainable use and protection of water and marine resources; 4) the transition to a circular economy; 5) pollution prevention and control; 6) the protection and restoration of biodiversity and ecosystems (Bakir et al., 2020). To be considered sustainable under the EU taxonomy, the activity needs to substantially contribute to one of the environmental objectives, however, it also must "do no significant harm" to any other objective (Dusík and Bond, 2022; Lucarelli et al., 2020). Further, it more clearly defines "green", and gives a clear definition by which companies, investors and policymakers can be considered as such. It is likely that the taxonomy will lead to increased investment in activities that are classified as sustainable under the taxonomy, and that investors will be increasingly concerned to which extent the business is compliant with the taxonomy. Thus, businesses with partners around the world may ensure that the taxonomy influences markets outside EU borders.

5. Fish meal: dependence or convenience?

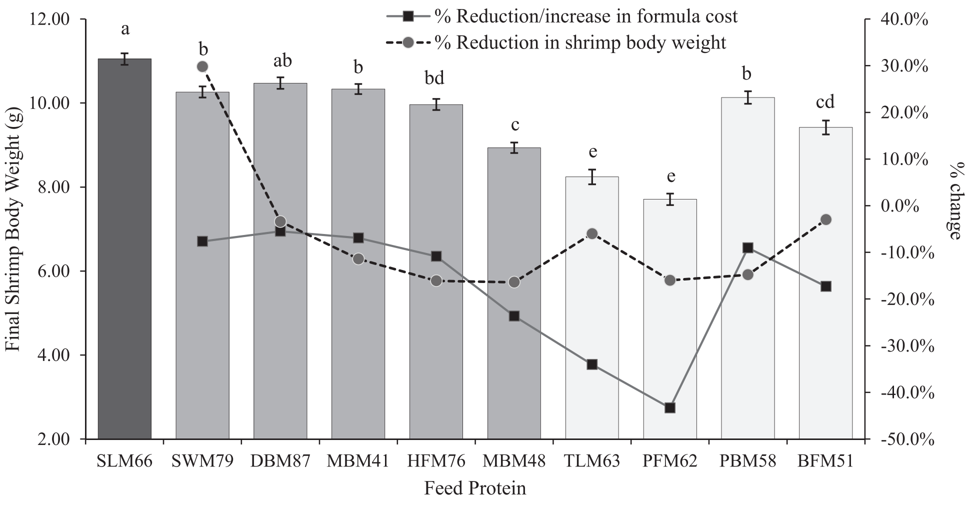
5.1. From the perspective of nutrient contribution in formulations

Fish meal carries a high energy and nutrient content for marine shrimp with a composition that few other commercially available feed ingredients are able to match. It is rich in digestible protein, EAAs, n-3 PUFA, cholesterol, phospholipids, and minerals. The contribution of fish meal in meeting the levels of essential nutrients set in shrimp feed recipes can be significant, which partially offsets its high costs. Therefore, the use of fish meal may still remain cost-competitive depending on its market price, nutrient profile, dietary inclusion level and marketed value of the finished feed. Fish meal can also perform well as a feed attractant and palatability enhancer (Nunes et al., 2006; Nunes et al., 2019).

Over the past 30 years, the use of fish meal in shrimp feeds has drastically reduced from more than 25 % in the 1990 ́s to an average of 12 % or less in the past decade (Tacon and Metian, 2008; Naylor et al., 2000). There is also an ongoing shift from fish meal made from forage fish to cheaper and more locally available sources of fish meal. These are fish meals made from fish waste (trimmings and offal) and by-products of the fish processing industry obtained from capture fisheries (tuna, sardines) and aquaculture (tilapia, salmon, pangasius). Projections indicate the usage of this type of fish meal in aquafeeds will increase from 22 % to 28 % between 2018 and 2030, respectively (https://www.fao.org/documents/card/en/c/ca9229en/).

In some countries, a "paradigm of essentiality" related to fish meal in shrimp diets has also persisted over the years within the industry. There is a fear that biological performance can be impacted if fish meal is reduced or completely withdrawn from shrimp feeds. In addition, some shrimp farmers perceive feed quality by their physical attributes, appearance, smell, and rapid detection and intake by shrimp. Some of these aspects do not correlate with feed nutrient composition. For example, farmers prefer feeds that look intact, smooth, and polished with a consistent dark brownish color and fish odor. When delivered in ponds, pellets should not have any floatability and sink immediately in the water column. No trail of oil should be detected in the water surface, and feed stimulation and intake by shrimp must occur immediately. Feeds with low fish meal levels may deviate in one or more of these standards, which may lead to farmer ́s dissatisfaction forcing feed mills to continue relying on high levels of fish meal.

From a nutrient-base formulation, fish meal can be replaced, partially or completely, in a cost-effective way with alternative feed proteins, as long as proper attention is given to the dietary level and digestibility of key nutrients. This makes the formulation process more complex and time-consuming as crude and digestibility levels of energy, protein, EAAs and total lipids from each raw material needs to be estimated. However, this is imperative to balance feed performance since most commercially available feedstuffs contain low level of essential nutrients and are also less digestible than fish meal (Tantikitti, 2014). If the focus is primarily put on gross nutrient levels, such as CP and total lipids, feed performance will be severely deteriorated despite significant cost savings (Fig. 3). As an example, fish meal replacement with poultry and feather meal (PFM62) led to a 16 % reduction in formulation cost, but also to a 43.3 % reduction of shrimp final body weight. This was



Ingredient		Dietary inclusion (% of the diet, as-is)	
		SLM	Animal by-product
SLM66	Salmon by-product meal, 66% CP	14.37	-
SWM79	Swine plasma meal, 79% CP	7.00	9.67
DBM87	Spray-dried blood meal, 87% CP	8.80	7.00
MBM41	Meat and bone meal, 41% CP	6.32	12.95
HFM76	Hydrolysed feather meal, 76% CP	3.98	14.39
MBM48	Meat and bone meal, 48% CP	1.75	17.72
TLM63	Tilapia by-product meal, 63% CP	-	15.12
PFM62	Poultry and feather meal, 62% CP	-	15.27
PBM58	Poultry by-product meal, 58% CP	-	16.24
BFM51	Brazilian fish by-product meal, 51% CP	-	18.67

Fig. 3. Final body weight (BW) of *L. vannamei* after 72 days of culture in a clear-water system. Shrimp of 2.03 ± 0.21 g were stocked with 70 animals/m^2 in 50 tanks of 500 L. Shrimp were fed isonitrogenous (35.88 % crude protein, CP) and isolipidic (7.88 % total lipids, as-is basis) diets with a partial or complete replacement of salmon by-product meal (SLM66, dark grey column) by animal by-product meals (light grey and white columns). Common letters indicate non-statistically significant differences in shrimp BW at $\alpha = 0.05$ according to Tukey ́s HSD test. Lines indicate the percentage change in shrimp BW (dotted line) and formula costs (solid line) in relation to the diet with 14.37 % SLM66. Permission to use the data has been given by the first author (Santos, P.H.Gd, Avaliação de subprodutos do abate de animais terrestres e de resíduos do processamento de peixes como fonte de proteína em rações para o camarão branco do pacífico, Litopenaeus vannamei (BOONE, 1931). Dissertation. Universidade Federal do Ceará, Instituto de Ciências do Mar, Fortaleza, 2013. p. 1–77.).

likely driven by the deficiency of one or more EAAs, fatty acids, and (or) lower digestibility and attractability of the finished feed.

Preferably, when replacing fish meal, one should rely on more than one, or on a combination of, substitute protein sources to reduce the dependence of nutrients derived from fish meal. From a nutrient perspective, replacement of fish meal for other ingredients has to ensure a proper level, balance and bioavailability of essential nutrients. However, if shrimp growth performance and feed conversion ratio (FCR) still deteriorate, then this can be the result of other factors, including poor feed attractiveness and palatability (Tacon et al., 2013). As indicated previously, both plant and land animal proteins provide little or no feeding stimulation to marine shrimp, which therefore requires the use of strong feeding effectors.

5.2. From the perspective of feed stimulation

One of the problems of feeding marine shrimp is the fact that they are predominantly benthic feeders, meaning they feed on the bottom of the water. To visualize their feeding behaviour is nearly impossible in a pond setting, since culture water has poor visibility, i.e., between 30 and 40 cm from the water surface (Darodes de Tailly et al., 2021). Therefore, blind feeding is usually carried out in farms with the assumption that the feed is delivered at the correct place, time and that the ration size is sufficient to reach near satiation of all the stocked population. However, commercial grow-out ponds are large in size, occupying areas that can range from less than 1 to more than 20 ha (1 ha = 10,000 m2), depending on the level of intensification. Shrimp will also move within the culture area throughout the day avoiding shallow areas with low DO concentrations and high transparency.

In practice, the lower the shrimp stocking density, the more scattered animals will be in the pond, which increases the risk of feed wastage. To ensure that feed is accessible to most of the stocked population, farmers broadcast feed manually or mechanically throughout the pond surface. In other cases, feeding trays positioned strategically in the pond will be used as an indicator of feed intake or used to exclusively deliver feed (1 tray/ha for each 10,000 stocked shrimp). Finally, the use of fixed automatic feeders has become popular in some countries. However, one mechanical feeder is able to cover a limited pond area, between 606 and 657 m2 allegedly sufficient to feed between 250,000 to 300,000 shrimp per day (Molina and Espinoza, 2018).

Irrespective of the feeding method used, feeds need to have the ability to stimulate shrimp feeding activity since their vision is rudimentary. Food is detected by cuticular chemosensory structures concentrated at the end of the body on antennules, mouthparts, chelae, antennae, and maxillipeds (Eap et al., 2020). Shrimp foraging activity is stimulated by low concentrations of organic compounds in the water such as free AAs, nucleotides, nucleosides, quaternary ammonium compounds, phospholipids, and biogenic amines. When present in feeds, these chemical drivers are capable of introducing a recurrent burst on shrimp´s normal feeding activity, trigger feed search and ingestive stimuli, i.e., detection and movement towards the food source and feed intake (Nunes et al., 2006). Marine proteins are known to contain these compounds at various concentrations.

However, fish meal-challenged diets appear to slow down shrimp feeding responses, increase feed wastage and FCR, unless feeding effectors are used. Commercial shrimp feeds can lose between 4 % and 5 % per hour of their dry matter content and more than 13 % per hour of CP after immersion in seawater (Carvalho and Nunes, 2006). As such, there is a general agreement that a shorter feed exposure to water can deliver increased amounts of nutrients to stocked shrimp, reduce nutrient leaching and minimize organic loading to the pond bottom. Thus, the dietary supplementation with feeding effectors has been the most common approach to enhance feed attractability and palatability of low fish meal shrimp feeds.

6. Use of krill meal as a feeding effector and growth enhancer

There has been a growing use of feeding effectors in commercial shrimp feeds with the corresponding reduction in the dietary inclusion of fish meal. Most of the marine feeding effectors traditionally used in shrimp feeds have been derived from small-scale facilities. These can face disruptions in product availability, price and quality (Zhu et al., 2019). This instability poses a risk to the consistency in performance of commercial feed formulations. Moreover, much of the documented studies on the effectiveness of these feeding effectors were derived from the 1980´s, when shrimp feeds were not constrained in the use of fish meal. Therefore, their effectiveness needs to be re-evaluated with feeds containing restricted levels of fish meal and updated nutrient profiles.

In the recent literature, krill meal has been the most studied feeding effector for shrimp. Krill meal has been recognized as a strong feed attractant and palatability enhancers for penaeid shrimp in various studies (Table 5). Nunes et al. (Nunes et al., 2019) ranked krill meal as the best feeding effector and growth enhancer for *L. vannamei* among six other marine ingredients, i.e., salmon meal, squid meal, shrimp head meal, shrimp meal, squid liver meal, and sardine hydrolysate. Also, krill meal has been found to increase feed palatability in marine shrimp by prolonging the feeding bout and the amount of feed eaten (Derby et al., 2016). In feeds formulated with 20 % poultry meal and no fishmeal, 3%

Table 5
Selected marine raw materials and their reported effects on the feeding and growth of farmed penaeid shrimp.

Species	Marine raw materials	Reported effect		Authors
Litopenaeus stylirostris	Krill meal and squid meal	Enhanced feeding	Increased growth	(Suresh and Nates, 2011)
Litopenaeus vannamei	Squid meal	–	yes	(Cruz-Ricque et al., 1987; Cruz-Ricque, E. G., Jean, Facteur de croissance de la farine de calmar pour la crevette japonaise: localisation de ce facteur. Conseil International pour l'Exploitation de la Mer. Comité Mariculture 1983. 14: p. 13.)
	Squid meal	–	yes	(Guillaume et al., 1989)
	Fish and krill hydrolysate	–	yes	(Córdova-Murueta and García-Carreño, 2002)
	Squid liver meal and squid hydrolysate	yes		(Nunes et al., 2006)
	Salmon hydrolysate	yes		(Grey et al., 2009)
	Krill meal and squid meal	yes	yes	(Sá et al., 2013)
	Krill meal	yes		(Derby et al., 2016)
	Krill meal		yes	(Sabry-Neto et al., 2017)
	Krill meal	–	yes	(Nunes et al., 2019)
	Krill meal	yes	yes	(Soares et al., 2021)
	Krill meal	–	yes	(Ambasankar et al., 2022)
Penaeus monodon	Crustacean and krill meal	yes	yes	(Smith et al., 2005)
	Shrimp head meal and krill meal	yes	yes	(Williams et al., 2005)

of krill meal significantly improved feed attractability, palatability and growth of juvenile *L. stylirostris* (Suresh and Nates, 2011). In all plant-based feeds for *L. vannamei*, a 1 % dietary inclusion of krill meal increased feed intake, while a significant enhancement in shrimp growth, yield and FCR was detected at 2 % (Sabry-Neto et al., 2017). However, Nunes et al. (Nunes et al., 2019) speculated that the growth enhancement factor observed in krill meal was likely a balance between a higher feed attractiveness and stimulation, and its contribution to the supply of key dietary nutrients.

7. Formulating fish meal-challenged feeds

The most straight-forward practical approach to reduce shrimp feed costs has evolved in the area of protein replacement of fish meal. Fish meal typically contains between 60 % and 72 % protein, thus a dietary inclusion of 12 % will contribute with only 20–25 % of the total CP content of a grower shrimp feed containing 35 % CP. However, a 12 % inclusion of fish meal will account for more than 1/4 of the total formula cost (assuming a total formula cost of USD 606/mt and a fish meal price of USD 1280/mt). Therefore, the higher the dietary inclusion and market cost of fish meal the greater is the opportunity to reduce feed costs.

There have been numerous investigations in the area of shrimp nutrient requirements, which has allowed nutritionists to better formulate on a least-cost basis. The major setback when fish meal is reduced is often noted at the farm level through a declining shrimp growth performance. Farmers often try to compensate slower shrimp growth rates with greater feed inputs which raises FCR, production costs and leads to a higher load of nutrients in water. However, replacement of fish meal for alternate ingredients can be overturned, as long as formulation can be optimized to account for all the essential nutrients on a digestible basis.

The first aspect to consider in the reduction or complete withdrawn of fish meal in shrimp feeds involves the identification of cheaper protein sources. Seasonal availability, quality (freshness) and individual ingredient costs may vary considerably between batches, manufacturers or regions. Therefore, cost-optimization of formulas need to be customized for each individual feed mill once potential alternate protein ingredients are sourced. In general, the most accessible alternate proteins to fish meal are meals and concentrates made from soybean, corn and wheat, and proteins from the animal rendering industry. The effective partial or complete replacement of fish meal on a cost-basis will depend on their market prices which need to be more than 50 % lower than fish meal, depending on their nutrient levels and composition. Once their unit cost is known (in USD per kg or mt), these ingredients will need to be chemically analyzed (crude protein, lipids, ash, total fiber, energy, moisture, AAs, fatty acids, phospholipids, vitamins, and minerals) and their digestibility estimated. This data is normally obtained through wet chemistry, NIRS (Near-Infrared Reflectance Spectroscopy) or in the case of digestibility, compiled from published data (Anon, 2011). A database containing the complete nutrient specifications for each individual ingredient (shown in Table 6) will need to be prepared and inserted in the formulation system, along with their individual price. The minimum and maximum dietary inclusion levels of each ingredient will also need to be defined which is dependent on the dietary tolerance of the shrimp species and on the manufacturing equipment available. The formulator also needs to set the nutrient levels to be reached in the finished feed. These levels can be fixed, or range values adopted (minimum or maximum), e.g., minimum of 30 % digestible protein, or vary within a certain range, e.g., 7–8 % total lipids.

Once these conditions are set, formulas can be designed on a nutrient and digestible basis. The formulation system will try to meet pre-defined nutrient levels (on a gross and nutrient basis) by combining the different feed ingredients and additives available at the lowest economical cost possible. As such, the dietary inclusion of ingredients with a lower price will only be favoured, if the dietary inclusion of fish meal is not cost-competitive. For example, a diet containing 10% fish meal and 2% krill meal is less cost-effective compared to a diet with no fish meal and 4% krill meal (fish meal price was set at USD 1750/mt, Table 7). This can change, if fish meal prices increase 5, 10, or 15%. These diets contain nearly the same level of digestible protein, and EAAs (lysine, methionine, and methionine plus cysteine). Krill meal is used to supply key essential nutrients, such as cholesterol, phospholipids, and n-3 PUFAs, and to compensate for a lower feed attractiveness and palatability as fish meal levels are reduced. Therefore, feed performance is likely to be kept the same while providing significant cost savings.

Table 6

A typical ingredient nutrient specification used in feed formulation with data from (Vieira et al., 2022) and (Nunes et al., 2019).

Nutrients/ Ingredients	Salmon by-product meal	Poultry by-product meal	Corn gluten meal	Krill meal, full-fat	Soy protein concentrate
Proximate composition (%)					
Dry matter	89.11	93.62	93.34	91.63	93.04
Crude protein	64.44	62.87	57.38	57.90	62.24
Digestible protein	50.87	39.47	27.25	48.81	49.35
Total lipids	8.71	13.60	7.83	25.16	1.20
Total fiber	0.21	0.30	1.05	3.06	4.60
Ash	16.12	14.40	2.47	8.55	6.60
Gross energy MJ/kg)	20.14	21.56	22.01	24.66	19.08
Digestible energy (MJ/kg)	16.94	10.00	15.41	19.87	15.65
Minerals (%)					
Calcium	3.33	4.71	0.01	1.25	0.35
Phosphorous	2.52	2.48	0.49	1.23	0.67
Magnesium	0.20	0.18	0.09	0.60	0.29
Fatty acids (%)					
LNA (18:2n-6)	1.13	2.65	4.54	0.50	0.61
LOA (18:3n-3)	0.32	0.14	0.05	0.40	0.08
EPA (20:5n-3)	0.67	–	–	4.32	–
DHA (22:6n-3)	0.99	–	–	2.20	–
Phospholipids (%)	–	–	–	10.06	–
Cholesterol (mg/kg)	422	105	–	6290	–
Amino acids (%)					
Arginine	3.91	4.12	1.93	3.39	4.59
Histidine	1.77	1.00	1.27	1.24	1.61
Isoleucine	2.67	2.53	2.29	2.87	2.88
Leucine	4.36	4.46	9.22	4.42	4.79
Lysine	4.97	2.65	1.01	4.03	3.76
Methionine	1.87	0.93	1.51	2.00	0.81
Methionine + Cystine	2.70	2.73	2.57	2.43	1.68
Phenylalanine	2.51	2.55	3.50	2.93	3.20
Threonine	2.76	2.52	1.94	2.43	2.40
Tryptophan	0.57	0.50	0.33	0.75	0.81
Valine	3.31	3.32	2.68	2.91	3.00
Digestible amino acids (%)					
Arginine	3.24	2.69	1.34	2.97	4.02
Histidine	1.31	0.74	0.76	1.04	1.30
Isoleucine	1.90	1.45	0.98	2.51	2.19
Leucine	3.27	2.61	3.48	3.76	3.66
Lysine	4.06	2.08	0.84	3.63	3.18
Methionine	1.51	0.74	0.87	1.87	0.57
Methionine + Cysteine	1.98	1.45	1.50	2.05	1.14
Phenylalanine	1.77	1.49	1.46	2.51	2.44
Threonine	2.04	1.48	0.97	2.03	1.81
Tryptophan	0.37	0.29	0.23	0.63	0.59
Valine	2.39	1.75	1.32	2.46	2.25

Table 7
Cost analysis of fish meal (FM) elimination in shrimp diets with progressive supplementation with krill meal.

	Price[a]	Ingredient Composition (% of the diet, as-is)				
Ingredients	(USD/ mt)	10 % FM	7.5 % FM	5 % FM	2.5 % FM	0 % FM
Soybean meal	580	34.16	46.00	46.30	48.00	48.00
Wheat flour	450	28.65	23.63	23.40	21.85	21.16
Salmon by-product meal[b]	1750	10.00	7.50	5.00	2.50	–
Soy protein concentrate[b]	1150	9.25	–	–	2.51	3.27
Poultry by-product meal[b]	1080	3.08	7.77	11.14	8.21	9.18
Wheat gluten meal	2200	3.00	2.16	1.70	1.37	2.00
Calcium carbonate	475	2.01	1.01	–	0.45	0.55
Krill meal, full-fat[b]	3000	2.00	2.50	3.00	4.00	4.00
Corn gluten meal[b]	900	1.75	3.50	3.21	5.00	5.00
Soy lecithin oil	1500	1.50	1.44	1.36	1.21	1.21
Salmon oil	2300	1.43	1.72	2.05	2.12	2.72
Monocalcium phosphate	1300	1.40	1.00	1.00	0.98	0.98
Salt	70	0.88	0.88	0.88	0.88	0.88
Mineral-vitamin premix	5000	0.30	0.30	0.30	0.30	0.30
Synthetic binder	1800	0.20	0.20	0.20	0.20	0.20
DL-Methionine, 99 %	3000	0.19	0.20	0.21	0.22	0.24
Choline chloride, 60 %	1150	0.11	0.11	0.11	0.11	0.11
Vitamin C, 35 %	12,200	0.10	0.10	0.10	0.10	0.10
L-Lysine, 54.6 %	2150	–	–	0.03	–	0.11
Formula cost (USD/ mt)	–	**905**	**860**	**858**	**854**	**858**
5 % increase in fish meal price	–	914	866	863	856	858
10 % increase in fish meal price	–	923	873	867	858	858
15 % increase in fish meal price	–	931	879	871	861	858
Basic nutrient composition						
Dry matter	%	90.01	90.00	90.10	90.22	90.41
Crude protein	%	36.80	37.59	38.00	38.00	38.00
Digestible protein	%	30.00	30.00	30.00	30.00	30.00
Gross energy	MJ/kg	17.09	17.37	17.68	17.59	17.73
Digestible energy	MJ/kg	13.00	12.77	12.77	12.86	12.94
Total lipids	%	6.00	6.95	7.54	7.28	7.80
Ash	%	9.57	8.84	8.00	7.99	7.88
Total fiber	%	3.12	3.59	3.63	3.89	3.92
Lysine	%	2.10	2.10	2.10	2.07	2.07
Methionine	%	0.80	0.80	0.80	0.80	0.80
Methionine + cysteine (M+C)	%	1.43	1.49	1.53	1.50	1.51
Digestible lysine	%	1.81	1.82	1.82	1.81	1.81
Digestible methionine	%	0.50	0.50	0.49	0.48	0.46
Digestible M+C	%	0.93	0.96	0.96	0.94	0.93

[a] 2022 prices
[b] Composition presented in Table 6

8. Conclusion

This review aimed to address marine resource replacement in shrimp feed formulations, current industry practices and their challenges. It has used the dietary inclusion of krill meal as an example on how to optimize low fish meal diets and use its properties as a feed additive to increase feed consumption and growth of shrimp already at low inclusion levels. It is therefore one of the options that can be used as a formulation tool to decrease the reliance on fish meal, which opens the way for alternative ingredients that improve the cost efficiency and sustainability of feeds.

CRediT authorship contribution statement

Alberto J.P. Nunes: Writing – original draft, Software, Formal analysis, Visualization. **Lise Lotte Dalen:** Writing – original draft, Formal analysis, Visualization. **Geronimo Leonardi:** Writing – original draft. **Lena Burri:** Writing – original draft.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests, Lena Burri reports a relationship with Aker BioMarine AS that includes: employment. Lise Lotte Dalen reports a relationship with Aker BioMarine AS that includes: employment. Geronimo Leonardi reports a relationship with Aker BioMarine AS that includes: employment. Alberto J.P. Nunes reports a relationship with Aker BioMarine AS that includes: consulting or advisory.

Data Availability

Data will be made available on request.

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