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Review

The effect of aquaculture feed on the nutritional quality of farmed seafood: A review of feed ingredients and their impact on human health

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Abstract: Aquaculture has emerged as a primary source of global seafood production, with the nutritional quality of farmed seafood being significantly influenced by the composition of aquaculture feed. This review examines the impact of various feed ingredients—including fishmeal, plant-based formulations, and algae—on the nutritional profiles of farmed seafood, focusing particularly on key nutrients such as omega-3 fatty acids, protein quality, and essential vitamins. While fishmeal has traditionally served as a cornerstone in aquaculture feed due to its high-quality protein and omega-3 content, sustainability challenges have driven the adoption of alternative ingredients. Plant-based feeds, though widely available, may alter the nutritional composition of seafood by reducing omega-3 levels, while algae-based feeds offer a promising sustainable alternative capable of enriching seafood with essential fatty acids and bioactive compounds. Furthermore, the potential accumulation of contaminants such as heavy metals and persistent organic pollutants (POPs) in feed ingredients raises concerns about seafood safety and human health. This review underscores the need for optimizing feed formulations to balance nutritional quality, sustainability, and safety, thereby enhancing the health benefits of farmed seafood for consumers while addressing environmental concerns.

Keywords: aquaculture feed; farmed seafood; omega-3 fatty acids; fishmeal; plant-based feed; algae; seafood nutrition; human health

1. Introduction

The aquaculture sector plays an increasingly vital role in meeting the global demand for seafood, which continues to rise due to population growth and the recognized health benefits of seafood consumption. Farmed seafood now accounts for more than half of the world's seafood supply, a trend that underscores the importance of understanding factors influencing its nutritional quality [1,2]. Among these factors, the composition of aquaculture feed is pivotal in determining the nutrient profile of farmed species, including their omega-3 fatty acid content, protein quality, and essential micronutrients [3,4].

In 2009, aquaculture reached a significant milestone, with half of all fish and shellfish consumed by humans being farmed, surpassing the production of wild-caught fish. Despite this progress, the industry remains heavily dependent on fishmeal and fish oil, which account for 68% and 88% of global consumption, respectively [5]. To address sustainability concerns, there is ongoing research focused on replacing animal-based proteins, primarily fishmeal, with alternatives such as terrestrial plants, rendered animal products, krill, seafood by-products, or protist-derived materials. The National Organic Standards Board (NOSB) has recommended a 12-year phase-out of fishmeal and fish oil in organically certified aquaculture, reflecting both ethical and economic considerations [6].

Rising demand for fishmeal has significantly increased aquaculture feed costs. Moreover, using fishmeal to feed carnivorous species like salmon, rather than directly for human consumption, is increasingly seen as inefficient, given the resource limitations and feed conversion losses involved.

When exploring plant-based alternatives to animal-derived feeds, it is crucial to meet the essential amino acid (EAA) requirements of the fish while controlling carbohydrate levels, particularly simple sugars, to avoid glycemic issues [7]. Moreover, anti-nutrients that could hinder digestion or nutrient absorption must be minimized to ensure fish health [8]. The fish's acceptance of the alternative diet is another important factor, as feed intake plays a critical role in optimizing growth. Furthermore, the economic viability of these alternative feeds must be considered for widespread adoption.

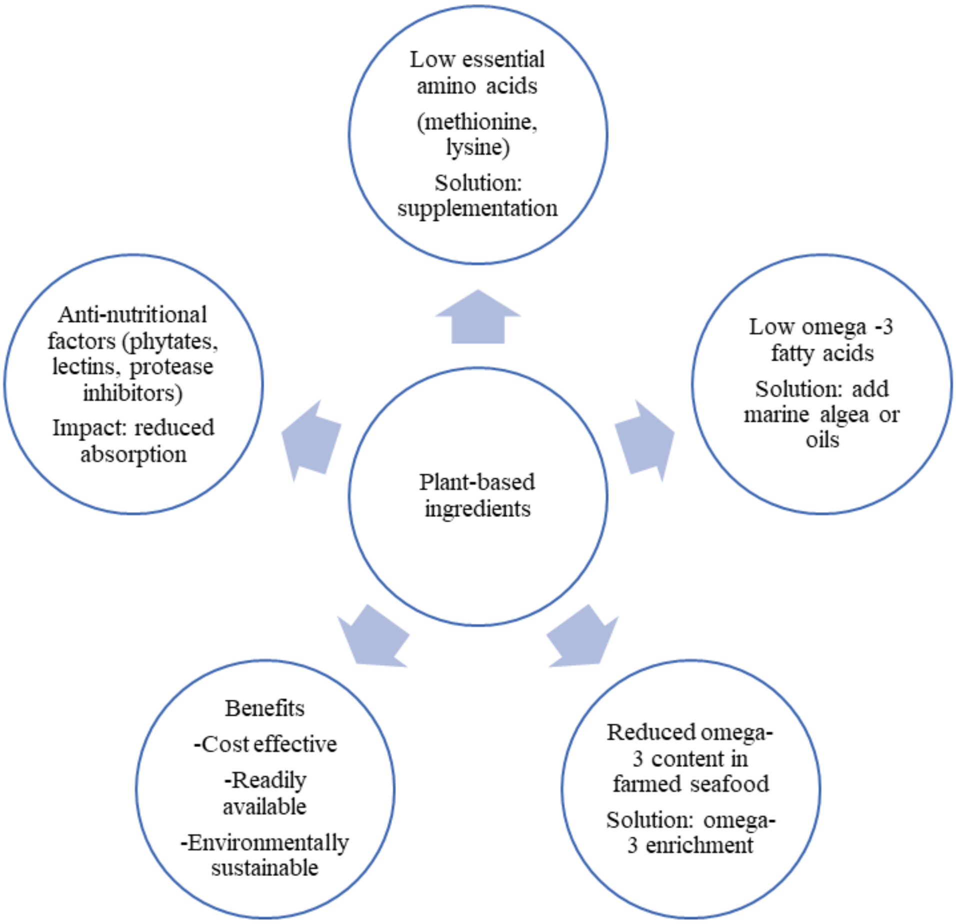

Figure 1. Plant-based feed ingredients in aquaculture.

While plant-based ingredients offer potential, they are not without challenges. Although plant-based ingredients contain low levels of essential amino acids and omega-3 fatty acids, along with anti-nutritional factors and reduced omega-3 content in farmed seafood, they are cost-effective, readily available, and environmentally sustainable (**Figure 1**). Issues such as hindgut inflammation, decreased appetite, and protease inhibition have been observed, particularly when plant proteins dominate the diet [9]. Reduced growth rates are also a concern when plant ingredients are used as the primary protein source [10,11]. Most studies on feed substitution have focused on specific dietary components, such as balancing amino acids [12], isolating anti-nutrients [13], or assessing fish health [14,15]. However, it is possible to formulate plant-based diets by combining complementary plant proteins, such as soy and maize, to meet the nutritional needs of fish [16,17].

Fishmeal and fish oil have traditionally been the primary components of aquaculture feeds, owing to their high protein content, digestibility, and abundance of long-chain omega-3 fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) [18,19]. However, the limited supply of fishmeal and fish oil, coupled with environmental sustainability concerns, has prompted a shift toward alternative feed ingredients such as plant-based proteins, terrestrial animal by-products, and algae. While these alternatives address the sustainability issue, they often result in nutritional trade-offs. For example, plant-based feeds are generally deficient in certain essential amino acids and omega-3 fatty acids, which can compromise the nutritional value of farmed seafood for human consumption [20-22].

Algae-based feeds have emerged as a promising alternative due to their high omega-3 fatty acid content and bioactive compounds, which can enhance the nutritional profile of seafood [23,24]. Furthermore, microalgae cultivation is considered environmentally sustainable, as it requires fewer resources and can be integrated into circular bioeconomy models [25,26]. Despite their potential, the high production costs and scalability challenges of algae-based feeds remain barriers to widespread adoption [27].

Another critical aspect of aquaculture feed is its potential to introduce contaminants, such as heavy metals, dioxins, and persistent organic pollutants (POPs), into the seafood supply chain [28]. These contaminants not only pose risks to human health but also raise questions about the safety and regulatory compliance of farmed seafood [29,30]. Consequently, there is a growing need for research into feed formulations that optimize the nutritional quality of seafood while minimizing safety risks and environmental impacts [22,31,32].

This review aims to provide a comprehensive analysis of how different aquaculture feed ingredients influence the nutritional quality of farmed seafood. Specifically, it examines the effects of feed components on omega-3 fatty acid levels, protein content, and the presence of contaminants, as well as the broader implications for human health. By synthesizing current knowledge and identifying research gaps, this review seeks to inform the development of sustainable and nutritionally optimized aquaculture feeds.

2. Types of feed ingredients in aquaculture and their nutritional implications

Aquaculture feeds serve as the foundation for the growth, health, and nutritional quality of farmed seafood. The choice of feed ingredients is critical, as it not only impacts the growth and yield of aquaculture species but also determines the nutrient profile of the final product for human consumption. Thus, examination of the primary types of feed ingredients used in aquaculture—fishmeal and fish oil, plant-based feeds, algae-based feeds, and emerging alternatives—and their implications for seafood nutrition needs to be explored.

2.1. Fishmeal and fish oil

Fishmeal and fish oil are considered the gold standards in aquaculture feed due to their rich content of high-quality protein and essential long-chain omega-3 fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These nutrients are crucial for the growth and immune function of aquaculture species, as well as for enhancing the health benefits of farmed seafood for human consumption [4,5]. Polyunsaturated fatty acids (PUFAs) are essential components in fish feed formulations, playing a vital role in the health, growth, and reproduction of aquatic species. PUFAs, particularly omega-3 fatty acids such as EPA and DHA, are crucial for maintaining cell membrane integrity, enhancing immune responses, and supporting optimal development in fish. They also improve the nutritional quality of aquaculture products, benefiting human consumers by providing heart-healthy omega-3s. Traditionally sourced from fish oil, the inclusion of PUFAs in fish feed is now being diversified through alternative sources such as microalgae, plant oils, and genetically modified crops to ensure sustainability. These innovations aim to reduce the environmental impact of fish feed production while maintaining the high nutritional value essential for aquaculture success [33,34].

Fishmeal, derived from small pelagic fish species such as anchovies and sardines, is highly digestible and provides a balanced amino acid profile that closely matches the requirements of many aquaculture species. However, concerns about the overexploitation of wild fish stocks for fishmeal and fish oil production have led to the exploration of sustainable alternatives [26,35].

Although fishmeal and fish oil are nutritionally superior, their inclusion in feed can also introduce contaminants such as heavy metals, dioxins, and polychlorinated biphenyls (PCBs), which may bioaccumulate in farmed seafood [28,36]. These contaminants pose risks to human health and highlight the need for stringent quality control measures in feed production [30,37].

2.2. Hybrid feeds

Hybrid (blended) feed ingredients, including soybean meal, corn seed, cotton seed, rapeseed, canola seeds, peanut seeds, guar plant, almond seed, black cumin seed, etc., have become widely used in aquaculture due to their availability, cost-effectiveness, and sustainability [21,31]. While these ingredients provide an alternative to fishmeal, they often lack certain essential amino acids such as methionine and lysine, which are critical for the growth and health of aquaculture species [38,39].

The nutraceutical potential of specific agricultural wastes, such as grape seeds, legumes, and cereals, can be harnessed in combination with other components, including Lactic Acid Bacteria (LAB)-fermented whey and medicinal herbs, to develop plant-based feeds for aquaculture. These innovative feed formulations not only promote the health of aquatic species but also contribute to human well-being. Additionally, their implementation offers significant environmental benefits, supports local economies, and delivers value to consumers [40].

In addition, hybrid feeds are generally low in omega-3 fatty acids, which can result in a reduced omega-3 content in farmed seafood. To address this issue, supplementation with omega-3-rich oils or marine algae is often necessary [9,41]. Moreover, the presence of anti-nutritional factors such as phytates, lectins, and protease inhibitors in hybrid feeds can impair nutrient absorption, leading to reduced feed efficiency, stunted growth, compromised immune responses, and overall diminished health in fish. These compounds interfere with the digestion and utilization of essential nutrients such as phosphorus, proteins, and amino acids, which are critical for optimal growth and physiological functions (**Figure 2**) [9,42].

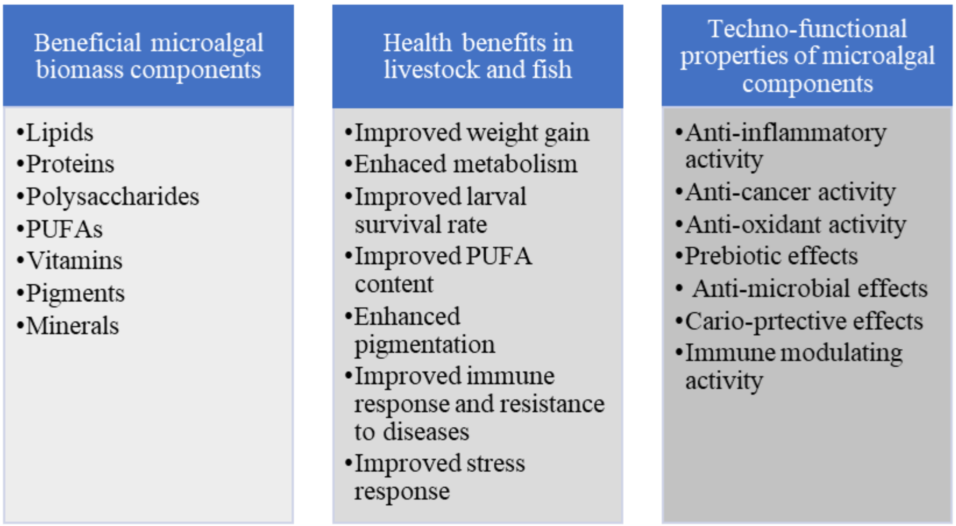

Figure 2. Effects of microalgae-based feed use in aquaculture (Adopted from Nagarajan et al. [43]).

2.3. Algae-based feeds

Algae-based feeds have garnered significant attention as a sustainable alternative to conventional feed ingredients in aquaculture. Currently, aquaculture utilizes around 40 different species of algae. Their nutritional profile, characterized by high levels of proteins, essential fatty acids, vitamins, and minerals, positions algae as a promising resource in aquafeeds. Depending on the species, algae may also serve as a source of bioactive compounds with potential health benefits for both farmed seafood and human consumers.

The high protein content in algae, ranging between 30% and 70% of dry weight, is one of its most attractive attributes for aquafeeds. Microalgae such as *Spirulina platensis*, *Chlorella vulgaris*, and *Nannochloropsis* are notable for their complete amino acid profiles, which include essential amino acids like lysine, leucine, and methionine [25,44]. These amino acids are critical for optimal growth, immune response, and stress resistance in aquatic species [45].

Moreover, algae-based proteins can partially replace fishmeal, reducing dependency on overexploited fish stocks while maintaining comparable performance in aquaculture production systems [22,26]. The digestibility of algal proteins in aquafeeds has also been found to be high, which enhances feed efficiency [46].

Microalgae are one of the primary sources of omega-3 long-chain polyunsaturated fatty acids (LC-PUFAs), such as EPA and DHA. Algae such as *Schizochytrium* and *Nannochloropsis* produce significant quantities of these LC-

PUFAs, which are essential for maintaining the health of farmed fish and enriching the nutritional quality of the final seafood product for human consumption [47]. Including algae in feed formulations has been shown to improve the fatty acid profile of aquaculture products, reducing the reliance on fish oil [26]. The inclusion of algae in aquafeeds enhances the fatty acid profile of farmed seafood, aligning it more closely with the nutritional qualities of wild-caught counterparts [48].

- Algae are a rich source of vitamins, including vitamins A, B-complex (e.g., B12, riboflavin, niacin), C, D, and E, which play critical roles in fish metabolism, immunity, and growth [49,50]. These micronutrients contribute to improved immune function and stress tolerance in farmed species [50,51]. The high iodine content in certain macroalgae, like kelp, may also contribute to thyroid health when incorporated into aquafeeds [49]. While vitamin C enhances immune responses and reduces stress in fish under intensive farming conditions [51], vitamin E acts as an antioxidant that protects cellular membranes from oxidative damage, improving the overall health and longevity of aquatic species [52]. Carotenoids such as astaxanthin, found in algae like *Haematococcus pluvialis*, serve as natural pigments that improve the coloration of farmed fish and shrimp, while also offering antioxidant and immunostimulatory benefits [53].
- Algae provide a wide range of essential minerals, including calcium, magnesium, phosphorus, iodine, selenium, and zinc, all of which are necessary for physiological processes in aquatic organisms [49]. For example, iodine from macroalgae such as kelp supports thyroid function and metabolic regulation and both zinc and selenium improve enzymatic activity and oxidative stress resistance [50,54]. The bioavailability of these minerals in algal biomass is high, ensuring effective absorption and utilization by aquaculture species (**Figure 2**) [44].

Algae are a source of numerous bioactive compounds, including carotenoids (e.g., astaxanthin), phycobiliproteins, and polysaccharides, which offer antioxidant, anti-inflammatory, and immunostimulatory properties. These compounds enhance the health and disease resistance of aquatic species, reducing the need for antibiotics and promoting sustainability in aquaculture practices (**Figure 2**) [52,55].

Algae contain bioactive compounds such as:

- Phycobiliproteins: Found in red and blue-green algae, these have antioxidant and anti-inflammatory properties [56].
- Polysaccharides: Compounds like carrageenan and alginate enhance the gut health of farmed species and act as immunostimulants, improving resistance to diseases [55].
- Polyphenols and sterols: These compounds reduce oxidative stress and promote cellular repair, contributing to the overall health of aquatic species [52].

Algae-based feeds can significantly reduce the environmental footprint of aquaculture by decreasing the reliance on fishmeal and fish oil, thus reducing pressure on wild fish stocks. Using non-arable land and saline or wastewater for cultivation, minimizing freshwater and land competition with terrestrial agriculture (**Figure 2**) [57].

Algal feeds also help lower nitrogen and phosphorus emissions in aquaculture systems, mitigating eutrophication risks [58,59]. Additionally, algae can improve feed conversion ratios and reduce waste in aquaculture systems, enhancing the overall sustainability of seafood production (**Figure 2**) [60].

Despite these advantages, the widespread adoption of algae-based feeds faces challenges, including high production costs, variability in nutritional composition, and the need for scalable cultivation technologies. Advances in biotechnology, such as genetic engineering and bioprocess optimization, may address these challenges and make algae a mainstream component in aquafeeds [58].

2.4. Application of *enzymes* as a feed additive in aquaculture

The use of enzymes as feed additives in aquaculture has garnered attention for its potential to enhance feed efficiency, improve nutrient utilization, and promote the health of aquatic organisms. Enzymes break down complex macromolecules into simpler, bioavailable forms, which significantly impacts the nutritional value of feed (**Figure 3**). Enzymes employed as feed additives in aquaculture are categorized based on the substrate they target:

Carbohydrases: Enzymes like cellulase, xylanase, and beta-glucanase degrade non-starch polysaccharides (NSPs), reducing their anti-nutritional effects and improving nutrient digestibility [61,62].

Proteases: Proteases enhance protein digestibility by hydrolyzing protein molecules into smaller peptides and amino acids [63,64].

Lipases: These enzymes facilitate the breakdown of dietary fats into glycerol and free fatty acids, leading to better lipid absorption [65].

Phytases: Phytases are crucial for releasing phosphorus bound in phytate, a major anti-nutritional factor in plant-based feeds [66,67].

Amylases: Amylases target starch, aiding in the breakdown of complex carbohydrates for energy [68,69].

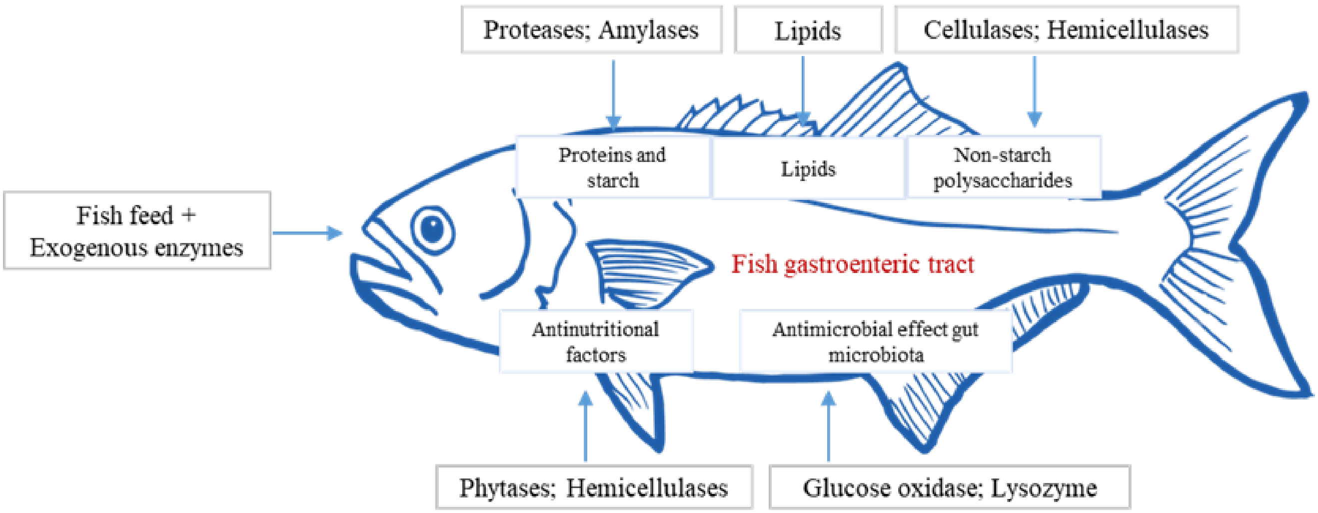

Figure 3. Application of enzymes as a feed additive (Adopted from Liang et al. [70]).

Enzymes function as biological catalysts that enhance the breakdown of macromolecules into absorbable forms:

Targeted Hydrolysis: Enzymes bind specific substrates (e.g., NSPs, proteins, lipids) and catalyze their degradation into simpler molecules.

Improved Digesta Properties: Carbohydrases lower digesta viscosity, facilitating better nutrient release and absorption [61].

Enhanced Nutrient Bioavailability: By breaking down complex compounds, enzymes improve the bioavailability of nutrients, including amino acids and phosphorus [71].

The inclusion of enzymes in aquaculture feed profoundly influences the nutritional value and overall performance of aquatic species:

Enhanced Nutrient Digestibility: Enzymes improve the digestibility of macronutrients and micronutrients, particularly in plant-based feeds where anti-nutritional factors like phytate hinder nutrient absorption. Phytases release bound phosphorus, while proteases improve amino acid availability [62,63].

Improved Feed Conversion Ratio (FCR): Enzyme supplementation results in better feed utilization and lower FCRs, enhancing aquaculture's economic viability [61,62].

Reduction of Anti-Nutritional Factors: Enzymes such as phytase and carbohydrases mitigate the effects of anti-nutritional factors like NSPs and phytates, increasing feed efficiency and nutrient retention [66,67].

Growth Performance: Improved nutrient digestibility contributes to faster growth rates, better specific growth rates (SGR), and higher weight gain in aquaculture species, such as tilapia and carp [63,65].

Environmental Benefits: Enzymes enhance nutrient absorption, thereby reducing nutrient excretion and environmental pollution. For example, phytase reduces phosphorus excretion, mitigating eutrophication risks in aquaculture systems [67,72].

Despite their benefits, enzymes face challenges in aquaculture applications:

Species-Specificity: Different species have unique digestive capabilities, requiring tailored enzyme blends [69].

Thermal Stability: The high temperatures involved in feed processing can denature enzymes. Coating and encapsulation technologies are being developed to address this issue [61].

Cost: The production of enzymes remains a financial barrier, particularly for small-scale aquaculture operations [42].

Advancements in biotechnology, such as genetically modified organisms for enzyme production and research on multi-enzyme complexes, offer potential solutions to these challenges. Enzymes as feed additives offer a sustainable and efficient approach to improving aquaculture feed. By enhancing nutrient bioavailability, reducing feed conversion ratios, and mitigating environmental impacts, enzymes are transforming the aquaculture industry. Continued research and technological innovations will further optimize their applications, making aquaculture more sustainable and profitable.

In addition to enzymes, the synergistic use of prebiotics and probiotics is gaining recognition in aquaculture. Prebiotics, such as oligosaccharides, serve as substrates that promote the growth of beneficial gut microbiota, while probiotics introduce live beneficial microorganisms directly into the digestive system. These approaches complement enzyme supplementation by improving gut health, enhancing the immune response, and further boosting nutrient absorption, ultimately contributing to better growth performance and disease resistance in aquaculture species [73,74].

2.5. Emerging alternative feed ingredients

As the aquaculture industry seeks to reduce its reliance on traditional feeds like fishmeal and fish oil, innovative feed ingredients are gaining attention for their sustainability and nutritional potential. These alternatives address environmental concerns and provide opportunities to diversify feed sources while maintaining or improving the growth performance and health of farmed aquatic species. Among the most promising emerging feed ingredients are insect meal, single-cell proteins (SCPs), and by-products from terrestrial animal processing. This section thoroughly explores these alternatives, focusing on their nutritional profiles, environmental benefits, and challenges.

2.5.1. Insect meal

Insect meal is rapidly emerging as a sustainable, nutrient-dense feed ingredient for aquaculture, with substantial potential to replace conventional fishmeal in aquaculture diets. The nutritional value of insect meal is considerable, as it provides high-quality protein, essential amino acids, lipids, and micronutrients that are crucial for optimal fish growth and health. Insects such as black soldier fly larvae (*Hermetia illucens*), mealworms (*Tenebrio molitor*), and crickets (*Acheta domesticus*) are particularly notable for their impressive protein content, typically ranging from 40% to 60% on a dry weight basis [75,76]. These protein levels are comparable to or even exceed those of conventional fishmeal, making them a viable alternative for aquaculture diets.

In addition to protein, insect meal is also rich in essential fatty acids, particularly omega-3 and omega-6 fatty acids, which are critical for maintaining fish health, promoting growth, and supporting immune function. Black soldier fly larvae, in particular, are noted for their balanced fatty acid profile, which closely mimics the composition of marine fish oils [77,78]. This nutritional profile makes insect meal an excellent substitute for fishmeal in aquaculture diets, especially given the increasing demand for omega-3 fatty acids in farmed fish.

From a sustainability perspective, the production of insect meal offers several environmental benefits over traditional fishmeal. Insects can be reared on organic waste materials, such as food scraps and agricultural by-products, which not only reduces the cost of feed but also addresses waste management challenges [79–81]. This rearing process significantly reduces the need for land, water, and other resources typically required in conventional animal protein production, thus lowering the overall environmental footprint of aquaculture feed. Furthermore, insect farming emits fewer greenhouse gases compared to fishmeal production from wild-caught fish, contributing to more sustainable aquaculture practices [82,83].

Numerous studies have demonstrated the potential of insect meal as a partial or complete replacement for fishmeal in aquaculture diets without compromising the growth performance, feed efficiency, or health of farmed fish. For example, studies showed that insect meal could replace up to 50% of fishmeal in diets for Atlantic salmon, rainbow trout, and tilapia, yielding similar growth rates and feed conversion ratios (FCRs) as fishmeal-based diets [75,84]. Additionally, studies found that insect-based feeds not only supported growth performance but also improved the fatty acid profile of the fish, enhancing the nutritional value of the farmed products [85,86].

However, despite its promising potential, the widespread adoption of insect meal in aquaculture faces several challenges, particularly related to scalability and consumer acceptance. Large-scale production of insects for feed is still in its infancy, and further research is needed to improve production efficiency and ensure cost-effectiveness at commercial scales [87]. Additionally, consumer acceptance of insect-based aquaculture products remains a barrier, as many consumers are unfamiliar with insect-based food sources and may be hesitant to consume products derived from insect-fed fish [88–90]. Overcoming these challenges will be critical for the long-term success of insect meal in the aquaculture industry.

In summary, insect meal holds great promise as a sustainable and nutrient-rich alternative to fishmeal in aquaculture. It provides essential nutrients such as high-quality protein, omega fatty acids, and micronutrients while also offering significant environmental benefits. With continued research and development to address scalability issues and consumer concerns, insect meal may become a key component of future aquaculture systems.

2.5.2. Single-cell proteins (SCPs)

Single-cell proteins derived from microorganisms such as bacteria, yeast, and fungi are highly promising for aquaculture feeds. SCPs are characterized by their exceptionally high protein content, reaching up to 80% of dry weight, making them a highly concentrated protein source for aquaculture species [91,92]. They provide a well-balanced profile of essential amino acids, including lysine, methionine, and threonine, which are critical for growth and metabolism in aquatic species [93]. Beyond protein, SCPs contain bioactive compounds such as nucleotides, β-glucans, and mannan-oligosaccharides, which contribute to improved gut health, immune system modulation, and disease resistance in farmed species [94,95].

The production of SCPs offers significant sustainability and scalability advantages. SCPs can be grown on various substrates, including agricultural and industrial by-products such as molasses, whey, lignocellulosic biomass, and even methane or carbon dioxide, reducing the competition with human food resources [92,96]. Such systems not only promote waste valorization but also minimize the carbon footprint of aquaculture feed production. SCP production processes are also relatively fast, allowing for rapid biomass generation and scalability to meet the growing demand for aquafeeds [97].

Studies have demonstrated the efficacy of SCPs in enhancing the performance of various aquaculture species. For example, SCP-based diets have improved growth rates, feed conversion ratios (FCR), and overall health in shrimp, salmon, tilapia, and catfish [93,98]. In shrimp, SCP diets enhanced survival rates and immune responses when exposed to pathogenic challenges [99]. Similarly, in Atlantic salmon, SCP supplementation improved growth performance and intestinal health while maintaining feed palatability [100]. SCPs have also been shown to support the growth of herbivorous fish such as tilapia, providing an alternative protein source that aligns with their dietary requirements [101].

Despite their advantages, the adoption of SCPs in aquafeeds faces challenges.

The high production costs, driven by fermentation technologies and downstream processing, remain a significant barrier [92]. Additionally, the scalability of production systems to meet global aquaculture demands requires further optimization. Consumer acceptance is another critical factor, as the use of microorganisms as feed ingredients may face initial resistance in some markets [102]. However, advancements in biotechnology, including genetic engineering and process optimization, are likely to enhance the feasibility and cost-effectiveness of SCP production, paving the way for their broader use in the aquaculture industry.

2.5.3. By-products from terrestrial animal processing

By-products from terrestrial animal processing, such as poultry by-product meal, blood meal, and other animal-derived materials, are gaining significant attention as cost-effective and sustainable alternatives to traditional fishmeal in aquaculture feeds. These ingredients provide an opportunity to repurpose agricultural waste streams, contributing to the circular economy while reducing reliance on marine resources.

Terrestrial animal by-products are nutrient-dense, offering high levels of protein (up to 70% in some cases), essential amino acids, and lipids, which are critical for the growth and health of aquaculture species [103,104]. For instance, poultry by-product meal contains well-balanced amino acid profiles, including lysine and methionine, comparable to fishmeal [41,105]. Blood meal, another widely used by-product, is particularly rich in lysine and iron, enhancing its value in protein supplementation [21,106,107]. Moreover, these by-products are a significant source of lipids and energy, essential for efficient feed conversion [103,108].

Numerous studies have demonstrated the effectiveness of terrestrial animal by-products in aquafeeds. Poultry by-product meal has been used successfully in the diets of tilapia, trout, and catfish, achieving growth performance and feed conversion ratios comparable to those observed with fishmeal-based diets [105,107]. In shrimp, partial replacement of fishmeal with blood meal or hydrolyzed feather meal has supported growth and survival rates while reducing feed costs [109–111]. Additionally, terrestrial by-products such as hydrolyzed collagen and gelatin have been explored for their bioactive properties, potentially enhancing immune function and stress resistance in aquaculture species [112,113].

Despite their nutritional value, several challenges limit the widespread adoption of terrestrial animal by-products in aquafeeds. Palatability issues, often linked to processing methods and residual odors, can affect feed intake in certain species [103,114]. Digestibility is another concern, as the high ash content in some by-products can reduce nutrient absorption and feed efficiency [104,107]. Moreover, the potential for bioaccumulation of contaminants, such as heavy metals, hormones, and antibiotics, necessitates stringent quality control measures to ensure the safety of these ingredients [111,113].

Advancements in processing technologies, such as enzymatic hydrolysis and extrusion, are improving the palatability and digestibility of terrestrial animal by-products [105]. Additionally, emerging research into bioactive peptides derived from these by-products could unlock new functionalities, including enhanced disease resistance and stress tolerance in aquaculture species [111,112]. With continued innovation and rigorous safety standards, terrestrial animal by-products have the potential to play a pivotal role in the sustainable development of aquaculture feeds.

2.5.4. Algae-based feeds

Algae-based feeds, discussed in detail in previous sections, also represent a critical part of emerging feed alternatives due to their high protein content, omega-3 fatty acids, and bioactive compounds [46,52]. These feeds are particularly promising for enhancing the nutritional value of farmed seafood while maintaining environmental sustainability.

3. Impact of feed on seafood nutrient profile

The type of feed used in aquaculture directly affects the nutritional composition of farmed seafood. Key nutrients impacted by feed composition include omega-3 fatty acids, proteins, and vitamins.

3.1. Omega-3 fatty acids

Omega-3 fatty acids are critical nutrients found in seafood, valued for their extensive health benefits, including cardiovascular protection, anti-inflammatory properties, and support for cognitive function [29,115]. These long-chain polyunsaturated fatty acids (LC-PUFAs), primarily EPA and DHA, accumulate in farmed seafood through their diet, predominantly sourced from fishmeal and fish oil [26,116].

The replacement of fishmeal and fish oil with plant-based feed ingredients has been associated with a decline in omega-3 content, particularly DHA, and an increase in omega-6 fatty acids in farmed seafood [22,26,31]. This shift in fatty acid composition is a concern for both consumer health and product quality. Studies have found that diets high in plant oils, such as soybean or rapeseed oil, reduce the deposition of omega-3 fatty acids in fish tissues [117,118].

To mitigate the omega-3 deficit in farmed seafood, supplementation with algal-derived oils has been identified as a sustainable and effective alternative [27,119]. Algal oils provide a direct source of DHA and EPA without relying on wild fish stocks, thereby addressing both sustainability and nutritional goals [51,120]. Moreover, recent advancements in algal cultivation technologies have significantly reduced costs, making algal oils more accessible for large-scale aquaculture applications [116,119].

3.2. Protein quality

The protein quality of farmed seafood is closely tied to the amino acid profile of its feed. Fishmeal, a traditional aquafeed component, is considered a gold standard due to its well-balanced composition of essential amino acids, including lysine and methionine, which are critical for growth and health [21,31].

While plant-based feed ingredients such as soybean meal offer a high protein content, they often lack specific essential amino acids or contain them in suboptimal proportions, potentially reducing the protein quality of the resulting seafood [121]. Soybean meal, for instance, is deficient in methionine, which can limit its application in high-performance diets [9,35]. Furthermore, anti-nutritional factors (ANFs) present in plant ingredients, such as phytic acid and protease inhibitors, can interfere with nutrient absorption and metabolism [9,21].

Research highlights that supplementing plant-based feeds with synthetic or crystalline amino acids can effectively address these deficiencies, restoring protein quality and supporting optimal growth and feed conversion ratios in aquaculture species [112]. Recent innovations in amino acid supplementation strategies, such as encapsulated delivery systems, further enhance the bioavailability and efficacy of these nutrients [31,122].

3.3. Vitamins and minerals

Vitamins and minerals are indispensable for the health of farmed fish and the nutritional quality of seafood. Critical micronutrients such as vitamins A, D, E, and minerals like selenium and zinc play essential roles in metabolic processes, immune function, and overall growth [123].

Fishmeal is an excellent source of bioavailable vitamins and minerals, making it a key ingredient in aquafeeds [124,125]. For example, fishmeal naturally provides high levels of selenium and vitamin D, which are critical for antioxidant defense and calcium metabolism, respectively [126]. In contrast, plant-based ingredients may lack sufficient quantities of certain micronutrients or contain ANFs that inhibit their bioavailability [9]. For example, phytic acid in soybean meal can chelate essential minerals like zinc and calcium, reducing their absorption [5,127]. Fortification of plant-based feeds with synthetic vitamins and chelated minerals has been shown to improve nutrient availability and meet the nutritional requirements of farmed fish [123].

4. Effect of different feed sources on the nutritional properties of fish

4.1. Protein content and amino acid profile

The protein content and amino acid profile of farmed fish are significantly influenced by the feed composition. Studies have demonstrated that plant-based feeds often result in deficiencies in essential amino acids such as lysine and methionine, which are crucial for growth and development. For instance, it is noted that rapeseed meal could serve as a protein source for Nile tilapia, but anti-nutritional factors like glucosinolates limited its use without detoxification [9]. To address such deficiencies, supplementing plant-based feeds with synthetic amino acids, which significantly improved growth in hybrid striped bass (*Morone chrysops* × *Morone saxatilis*) is suggestd [114].

In addition to plant-based feeds, alternative protein sources such as insect meal and microbial proteins have shown promising results. It is reported that black soldier fly larvae meal provided a high-quality amino acid profile, comparable to fishmeal, in rainbow trout diets [128]. Similarly found that single-cell proteins derived from microorganisms were effective in supporting the growth of European seabass (*Dicentrarchus labrax*) [129]. Another approach involves using fermented plant ingredients reported that fermented soybean meal improved digestibility and protein content in Atlantic salmon [130]. These findings highlight the potential of novel feed ingredients to maintain or enhance protein quality in aquaculture.

4.2. Fatty acid composition

The fatty acid composition of farmed fish, particularly the levels of omega-3 fatty acids such as EPA and DHA, is strongly influenced by the type of oil or fat included in the feed. Replacing fish oil with vegetable oils, such as canola oil, led to a reduction in omega-3 levels and an increase in omega-6 fatty acids in Atlantic salmon [26]. Similarly, linseed oil supplementation in carp diets increased alpha-linolenic acid (ALA) levels but decreased DHA content, illustrating the trade-off between different fatty acid sources [26]. Algae-based oils have emerged as a sustainable and effective alternative to fish oil for maintaining omega-3 levels in farmed fish. For example, trout fed algae-derived DHA oils retained comparable omega-3 fatty acid levels to those fed traditional fish oil diets [116]. Camelina oil, when used as a partial substitute for fish oil, could maintain the nutritional quality of rainbow trout fillets [131]. Insects also provide a potential source of omega-3-rich oils, and in fact, it was reported that insect oil supported omega-3 retention in yellowtail [132].

The use of innovative feed ingredients such as krill meal has also proven effective. Krill meal supplementation enhanced DHA and EPA levels in Atlantic salmon [133]. Conversely, feeding sea bream with saturated fats, such as palm oil, significantly reduced omega-3 content [117]. These findings emphasize the importance of carefully selecting feed fats to optimize the nutritional quality of farmed fish.

4.3. Micronutrients

Micronutrient levels in farmed fish, including essential vitamins and minerals, are significantly influenced by the composition of their feed. Traditional fishmeal is known to be a rich source of micronutrients, such as selenium, vitamin D, and iron; however, plant-based feeds often lack adequate levels of these nutrients. For instance, it is found that plant-based feeds resulted in lower selenium content in salmon, which required supplementation to maintain fish health and nutritional quality [134]. Similarly, deficiencies in vitamin D levels in trout fed soybean-based diets were corrected through feed fortification [135].

Moreover, anti-nutritional factors in plant-based feeds, such as phytate, can hinder mineral absorption. It is demonstrated that phytate in plant ingredients reduced the bioavailability of calcium and phosphorus in Nile tilapia, negatively affecting bone development [9]. In contrast, natural ingredients like algae have proven beneficial for enhancing micronutrient levels. For example, algae-based feeds enhanced zinc bioavailability in shrimp [136], while iodine-fortified diets increased iodine content in fish [137].

Vitamin supplementation has also been shown to effectively address deficiencies in farmed fish. Fortifying fish diets with vitamin A has been found to improve growth and increase tissue levels of this essential nutrient in rainbow trout [138]. Similarly, including astaxanthin-rich feeds enhanced both pigmentation and antioxidant levels in trout, which not only improved their market value but also enriched their nutritional profile [139]. These studies highlight the critical role of feed composition in influencing the micronutrient content of farmed fish and the potential for supplementation to address nutritional deficiencies.

4.4. Choline

Choline is an essential nutrient that is water-soluble and often grouped with the B-complex vitamins present in some animal and plant products such as milk and dairy products, meat, eggs, beans, and peanuts (**Figure 4**) [140]. Choline, recognized as an essential nutrient by the Institute of Medicine in 1998, is a vital compound that is synthesized in the human liver, though typically not in sufficient amounts to meet all physiological needs [140]. It exists as both fat- and water-soluble forms in various foods, playing a critical role in many biological functions. Choline serves as a major methyl donor in methylation reactions, which are essential for regulating gene expression and cell function [141]. Additionally, it is a key component of phospholipids, which are integral to cell membranes, and is involved in the synthesis of acetylcholine, a neurotransmitter crucial for memory, mood regulation, and muscle control [142,143]. Despite its endogenous production, dietary intake of choline is necessary to prevent deficiencies, which can lead to liver dysfunction, neurological disorders, and muscle damage [140].

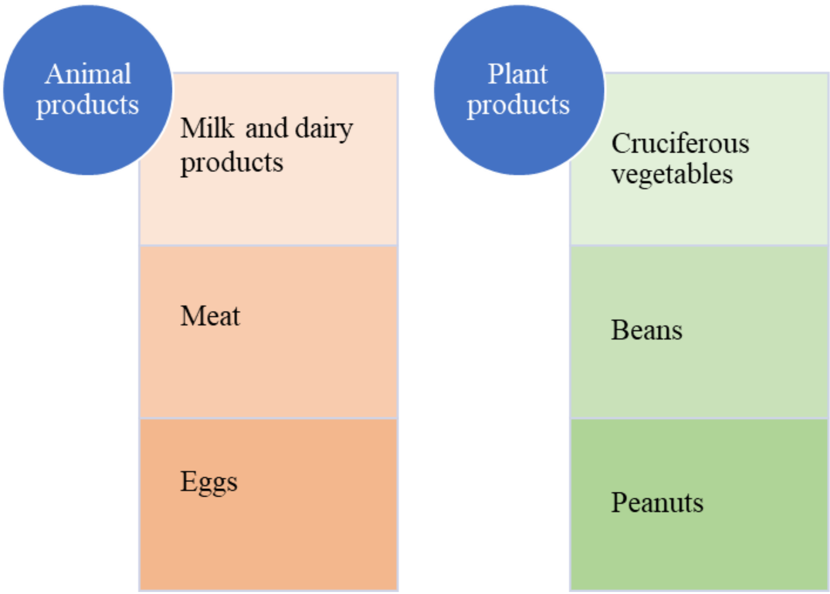

Figure 4. Choline sources from animal and plant products.

Choline is an essential nutrient that plays a critical role in numerous physiological processes, including neurotransmitter synthesis (acetylcholine), lipid metabolism, cell membrane integrity, and methylation reactions. It exists in various forms such as free choline, phosphocholine, and lipid-bound phosphatidylcholine. In seafood, choline contributes significantly to its nutritional profile, enhancing its value as a dietary component for human health. Choline intake supports brain development, cognitive function, and liver health, while deficiencies are linked to disorders such as fatty liver disease and impaired cognitive function [142,143].

For seafood, the choline content is influenced by the diet and feeding behavior of aquatic species. Fishmeal, a traditional feed ingredient, is rich in bioavailable choline, while plant-based and algae-based feeds may alter its levels depending on their composition and supplementation. Seafood enriched with choline supports consumer health by offering a natural source of this essential nutrient, particularly in populations with limited dietary diversity [144,145]. The incorporation of optimized feed formulations in aquaculture can help maintain or enhance choline levels in seafood, ensuring its health benefits are maximized.

Traditional fishmeal-based feeds, known for their high-quality protein and lipid content, are naturally rich in choline, leading to elevated levels in seafood. Conversely, plant-based feed ingredients, while more sustainable and cost-effective, often lack sufficient choline or its precursors, potentially reducing the nutrient content in farmed species unless supplemented. Algae-based feeds offer a promising alternative due to their bioactive compounds and high lipid content, enhancing the choline profile of aquaculture products. Wild seafood exhibits variability in choline levels based on the nutrient composition of natural prey. Optimizing feed formulations in aquaculture to include bioavailable choline sources is critical for improving seafood's nutritional quality, thereby enhancing its value as a dietary choline source for human health [142,144,145].

5. Concerns about seafood nutritional value

Seafood is renowned for its high nutritional value, serving as a rich source of high-quality protein, omega-3 fatty acids, and essential micronutrients such as iodine, selenium, and vitamin D. However, several factors can affect the nutritional profile of seafood, raising important concerns (**Figure 5**).

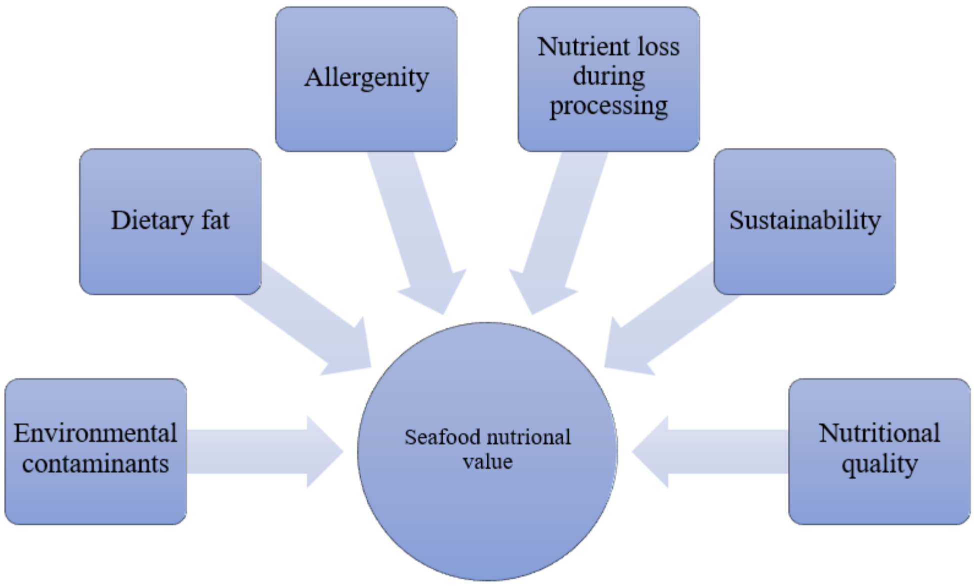

Figure 5. Factors affecting nutritional value of seafood.

5.1. Nutrient loss during processing

Processing methods such as freezing, smoking, or canning can lead to nutrient degradation. Heat-sensitive nutrients, such as vitamin C and certain B vitamins, are particularly vulnerable during thermal processing [146]. Additionally, smoked and canned seafood often contain elevated sodium levels, which may contribute to excessive dietary sodium intake, a known risk factor for hypertension and cardiovascular diseases [147] (**Figure 5**).

5.2. Sustainability and nutritional quality

Overfishing and unsustainable aquaculture practices threaten the availability of diverse and nutritionally valuable seafood species. Farmed fish often exhibit altered nutrient profiles due to differences in feed composition. For example, farmed fish may contain lower levels of omega-3 fatty acids than their wild-caught counterparts, depending on the diet provided in aquaculture systems [26]. Sustainable practices are crucial to maintaining both the ecological balance and the nutritional benefits of seafood (**Figure 5**).

5.3. Dietary fat imbalances

While seafood is a rich source of omega-3 fatty acids, concerns exist regarding the balance between omega-3 and omega-6 fatty acids in the modern diet. A high intake of omega-6 fatty acids relative to omega-3s, commonly observed in Western diets, may negate some of the cardiovascular and anti-inflammatory benefits of omega-3s [30]. Consumers need guidance on choosing seafood with optimal fatty acid profiles to maximize health benefits (**Figure 5**).

5.4. Allergenity

Seafood is among the most common food allergens, particularly shellfish and finfish, affecting approximately 2% of the global population [148]. Cross-contamination during processing or handling exacerbates risks for sensitive individuals. These challenges highlight the need for strict allergen management and labeling to ensure consumer safety (**Figure 5**).

6. Contaminants in aquaculture feed and their impact on human health

The quality of aquaculture feed directly affects not only the nutritional composition of seafood but also the potential accumulation of contaminants in farmed fish. Feed ingredients, particularly those derived from fishmeal, are known to harbor pollutants such as heavy metals, persistent organic pollutants (POPs), and other environmental toxins, which can bioaccumulate in fish tissues and pose health risks to consumers [149,150]. The risk is especially concerning for regular seafood consumers, as these contaminants can surpass safety thresholds over time.

The presence of contaminants in feed ingredients is a critical issue in aquaculture, influencing both the safety of farmed seafood and consumer health. Fishmeal and fish oil, widely used in traditional aquaculture feeds, can harbor heavy metals such as mercury, cadmium, and lead due to bioaccumulation in wild fish populations [28,149]. Persistent organic pollutants (POPs), including polychlorinated biphenyls (PCBs) and dioxins, are another concern in fishmeal and fish oil-based feeds. These contaminants can not only compromise the health of aquatic organisms but also lead to bioaccumulation in farmed seafood, creating risks for human consumption [151,152].

Plant-based feed ingredients are increasingly used as sustainable alternatives, but they are not devoid of contamination risks. Pesticides, herbicides, and mycotoxins, such as aflatoxins and fumonisins, have been reported in plant-based feed materials [153,154]. These contaminants may affect the growth and health of farmed aquatic species and potentially impact human health through the food chain.

Algae-based feeds are generally considered safe and sustainable, but their safety depends on the cultivation environment. Contaminants such as heavy metals, arsenic, and industrial pollutants can accumulate in algae, especially when grown in contaminated water sources [18,30]. Additionally, some species of algae are prone to producing harmful algal toxins, such as domoic acid and microcystins, which pose a risk to both aquaculture species and consumers [58,155].

Single-cell proteins and insect-based feeds, though emerging as promising alternatives, also have contamination challenges. Insect meal, for example, may contain pesticide residues if the insects were reared on contaminated organic waste, and pathogens such as *Salmonella* spp. and *Escherichia coli* can proliferate in improperly managed systems [75,156]. Similarly, the microbial origin of single-cell proteins raises concerns about endotoxins, mycotoxins, and other potential contaminants, particularly when fermentation substrates are sourced from industrial by-products [92,102].

To mitigate contamination risks, it is essential to implement stringent monitoring and quality control measures during feed production. Techniques such as hazard analysis and critical control points (HACCP) and regular contaminant screening can help ensure the safety of feed ingredients. Moreover, regulatory frameworks like the European Union’s Maximum Residue Levels (MRLs) and the Codex Alimentarius guidelines provide standards for acceptable contaminant levels in animal feed [58,157].

6.1. Food safety and contaminant levels

The type of feed used in aquaculture plays a critical role in determining the accumulation of contaminants in farmed fish, which has direct implications for food safety. While fishmeal-based feeds are often considered nutritionally rich, they are frequently associated with higher levels of environmental contaminants such as polychlorinated biphenyls (PCBs), dioxins, and heavy metals. Elevated PCB levels in salmon fed fishmeal, highlighting the potential risks to consumer health compared to fish fed plant-based diets [158]. Furthermore, fishmeal derived from wild-caught fish often contained mercury, which poses potential risks to consumers, especially considering the bioaccumulation of mercury in the food chain [159].

In addition to PCBs and mercury, fishmeal can also be a source of dioxins, persistent organic pollutants (POPs) that are harmful to human health. For instance, dioxin levels were significantly higher in farmed salmon fed fishmeal compared to those fed plant-based feeds [158]. Similarly, fishmeal from various sources had varying levels of contaminants, with higher levels typically found in fishmeal made from smaller wild-caught fish, which tend to accumulate more contaminants [160].

Plant-based feeds, on the other hand, generally contain lower levels of persistent organic pollutants (POPs). However, they can still introduce other contaminants into the food chain. The presence of pesticide residues in soybean-based feeds used for tilapia, underscoring the need for stringent quality control measures during feed production [150]. Similarly, improperly stored soybean meal used in aquaculture feeds could lead to mycotoxin contamination, specifically aflatoxins, which are potent carcinogens and present significant risks to both fish health and consumer safety a study [161].

The rise of alternative feed sources, such as algae and insect meal, has provided promising options for reducing the accumulation of contaminants in farmed fish. Algae-based feeds, for example, have been shown to significantly reduce levels of dioxins in salmon. The inclusion of algae in salmon diets resulted in a substantial decrease in dioxin levels, thus improving the safety profile of farmed fish [27]. Similarly, insect-based feeds contained lower levels of heavy metals and POPs compared to traditional fishmeal, further supporting the potential benefits of alternative feed ingredients for safer aquaculture [162].

Other studies have also reinforced the advantages of algae-based and insect meal feeds in mitigating the accumulation of environmental contaminants. Feeding rainbow trout with algae meal resulted in a significant reduction in mercury accumulation, highlighting algae's potential as a safer alternative to fishmeal [163].

In addition to these findings, researchers concluded that the quality of feed, particularly with regard to contaminant levels, is crucial for ensuring the safety and quality of aquaculture products [164]. These studies emphasized the need for careful sourcing, processing, and quality control of alternative feed ingredients to prevent contamination and guarantee the nutritional integrity of farmed fish.

In summary, the type of feed used in aquaculture significantly influences the level of contaminants accumulated in farmed fish. While fishmeal remains a primary source of nutrition, it is also associated with higher levels of harmful pollutants such as PCBs, dioxins, and mercury. In contrast, plant-based feeds and alternative ingredients such as algae and insect meal offer potential solutions for reducing these contaminants. However, ensuring the safety of these alternative feed sources also requires diligent monitoring for pesticide residues, mycotoxins, and other harmful substances.

6.2. Heavy metals

The bioaccumulation of environmental contaminants in seafood poses a significant concern. Heavy metals, such as mercury, and persistent organic pollutants (POPs), including polychlorinated biphenyls (PCBs) and dioxins, can accumulate in seafood, especially in predatory fish like tuna and swordfish [165,166].

Fishmeal is often sourced from small pelagic fish, which may bioaccumulate heavy metals like mercury (Hg), cadmium (Cd), and lead (Pb) from their environment. Mercury, particularly in the form of methylmercury, has been associated with neurotoxicity and developmental disorders in humans, while cadmium and lead exposure are linked to kidney dysfunction and cardiovascular diseases [167]. It was reported that fishmeal-based diets had significantly higher levels of mercury compared to plant-based or alternative feeds [167]. Mercury exposure has been linked to neurotoxicity and developmental delays, particularly in vulnerable populations such as pregnant women and young children [165,166]. The extent of contamination depends on the species, trophic level, and geographic region where the seafood is harvested.

6.3. Persistent organic pollutants (POPs)

POPs, including polychlorinated biphenyls (PCBs) and dioxins, are another major concern in fishmeal-based feeds. These contaminants originate from industrial processes and accumulate in aquatic ecosystems, entering the food chain through fishmeal [168]. Long-term exposure to POPs in humans has been linked to endocrine disruption, immunotoxicity, and cancer. Although plant-based and algae-based feeds are less likely to contain POPs, their contamination can still occur through agricultural runoff and improper processing [158].

6.4. Mycotoxins

Plant-based feeds can also pose contamination risks through mycotoxins, toxic secondary metabolites produced by fungi. Mycotoxins such as aflatoxins, deoxynivalenol, and fumonisins have been detected in soymeal and cereal-based feed ingredients, with adverse effects on fish health and potential carryover to human consumers. Proper storage, sourcing, and testing of feed ingredients are crucial to mitigate these risks [169].

6.5. Microplastics

Recent studies have highlighted the contamination of aquafeeds with microplastics, originating from the breakdown of larger plastic debris or additives used in feed packaging and processing. Microplastics can act as vectors for other contaminants, such as hydrophobic chemicals, potentially increasing the toxicological risks associated with seafood consumption [170].

6.6. Mitigation strategies

To reduce the accumulation of harmful contaminants in seafood, several strategies can be employed:

Stringent Quality Control: Ensuring the sourcing of high-quality feed ingredients with minimal contamination risks is paramount [171].

Alternative Feed Ingredients: Transitioning to plant-based or algae-based feeds with low contaminant profiles while maintaining nutritional adequacy is a promising approach [172].

Detoxification Processes: Employing technologies such as activated carbon adsorption or chemical treatments to reduce contaminant levels in raw feed materials [173].

Regular Monitoring: Establishing robust monitoring systems to evaluate feed and farmed fish for contaminants, ensuring compliance with safety standards [174].

Aquaculture feed plays a crucial role in determining the nutritional quality of farmed seafood. Fishmeal, plant-based ingredients, and algae all influence the nutrient profile of seafood, particularly omega-3 fatty acids, proteins, and vitamins. While fishmeal provides a high-quality source of omega-3s, its sustainability is a growing concern, leading to increased interest in plant-based and algae-based feeds. These alternatives can provide sustainable solutions for improving the nutritional quality of farmed seafood, though they may require supplementation to maintain optimal nutrient levels. Additionally, the potential for contaminants in aquaculture feed underscores the need for careful sourcing and quality control to ensure the safety of farmed seafood for human consumption. Further research is needed to optimize feed formulations that balance nutritional benefits, sustainability, and safety.

7. Challenges and future directions

Emerging feed alternatives face challenges that require attention to:

7.1. Cost and scalability

Alternative feed sources like single-cell proteins (SCPs), insect meal, and algae-based feeds need to be produced at a cost comparable to traditional feeds like fishmeal and soybean meal. Currently, these alternative ingredients are often more expensive due to factors such as the complexity of production, limited supply chains, and high processing costs.

Fishmeal and soybean meal are widely used because they provide a proven, reliable source of nutrition for aquaculture species and are economically viable on a large scale. For alternative feeds to be adopted on a global scale, they must not only match the nutritional benefits of traditional feeds but also be affordable. The challenge is ensuring that the production methods for SCPs, insect meal, and algae are cost-competitive.

SCPs, derived from microorganisms, have the potential to be a high-protein, sustainable alternative, but their production costs need to be reduced to compete with fishmeal prices. Similarly, insect meal is promising, but scalability and efficiency of large-scale insect farming are key hurdles [175].

7.2. Consumer acceptance

Public perception and regulatory frameworks must evolve to support the use of novel feed ingredients like insect meal and algae in aquaculture. Consumers and regulatory bodies may be hesitant to accept foods produced from animals fed with unconventional ingredients, particularly in Western markets where insects and algae may not yet be widely consumed.

Consumer confidence is crucial for the success of any new product, especially in the food industry. People may have concerns about the safety, quality, and ethical implications of using insect meal or algae-based feeds in the production of fish that will be consumed. Additionally, regulatory systems may not yet have established clear guidelines or approval processes for these novel ingredients.

Regulatory bodies, such as the European Food Safety Authority (EFSA) or the U.S. Food and Drug Administration (FDA), are still in the process of assessing and approving these alternative ingredients. Insects, for instance, are used in some regions for animal feed, but there may still be public skepticism regarding their safety or the acceptability of fish raised on such feeds [176].

7.3. Research and development

More research is needed to optimize feed formulations and understand the long-term effects of using alternative ingredients in aquaculture. This includes evaluating the nutritional profiles of alternative feeds, how they impact fish health, growth rates, and disease resistance, and how they affect human health when consumed.

Scientific validation is key for the widespread adoption of alternative feeds. There is a need for studies that ensure these feeds meet the nutritional requirements of different aquaculture species without compromising fish health or the quality of the final product. Additionally, research is needed to investigate the environmental and human health impacts of these new feed sources.

Researchers are investigating how algae- and insect-based feeds affect fish growth rates, disease resistance, and fat composition, which in turn can impact the nutritional quality of fish for human consumption. Long-term studies will be needed to confirm the sustainability of these feeds and their impact on the broader ecosystem.

Despite the challenges, the shift toward alternative feeds is crucial for achieving more sustainable aquaculture practices. The traditional reliance on fishmeal (often sourced from wild-caught fish) and soybean meal (which has its own environmental concerns) is not sustainable in the long term, especially as demand for seafood continues to rise. The adoption of more sustainable feed sources—like SCPs, insect meal, and algae—could reduce the environmental footprint of aquaculture by lowering reliance on wild fish stocks and reducing land-use pressures associated with soybean farming. Ultimately, overcoming these challenges will help align aquaculture with global environmental and nutritional goals, such as reducing greenhouse gas emissions, decreasing overfishing, and improving food security through more sustainable and nutrient-rich seafood production [98].

8. Conclusion

Aquaculture feed plays a crucial role in determining the nutritional quality of farmed seafood, influencing essential nutrients like omega-3 fatty acids, proteins, and vitamins, which are critical for human health. Traditionally, fishmeal has been the primary source of protein and omega-3s in aquaculture diets, providing a rich and high-quality nutrient profile for fish. However, the growing concern about the sustainability of fishmeal—stemming from overfishing, pressure on marine ecosystems, and competition with wild fish stocks—has spurred interest in alternative feed sources, including plant-based ingredients and algae-based feeds. These alternatives offer the potential to reduce the environmental impact of aquaculture by relying less on marine resources and by promoting more sustainable agricultural practices.

While plant-based feeds and algae-based feeds have shown promise in improving the sustainability of aquaculture, they may not provide the same nutrient composition as fishmeal. Plant-based ingredients often lack certain amino acids and essential fatty acids, particularly omega-3s, which are vital for fish health and the nutritional value of seafood. Algae, on the other hand, can be an excellent source of omega-3s, but the cost of cultivating algae at a large scale and the need for technological advancements to improve production efficiency still present significant challenges. Consequently, these alternative feeds may require supplementation with specific nutrients to meet the full nutritional requirements of farmed fish. The formulation of well-balanced, cost-effective feeds that are both nutritionally complete and sustainable remains a complex challenge.

Moreover, the potential for contaminants in aquaculture feed presents another important consideration. The sourcing of ingredients from plant-based or algae sources, as well as from insect farming, can introduce risks related to heavy metals, pesticides, or other harmful substances, which could ultimately impact the safety of farmed seafood for human consumption. This underscores the need for stringent quality control measures, traceability systems, and regular testing to ensure that alternative feeds meet safety standards and do not introduce harmful compounds into the food supply chain.

To address these concerns, continued research and innovation in aquaculture feed are essential. Future studies should focus on optimizing feed formulations that not only enhance the nutritional quality of farmed seafood but also ensure the sustainability of feed production. There is a need for in-depth investigation into the long-term effects of alternative feeds on fish health, growth rates, and disease resistance, as well as their impact on the nutritional quality of the final seafood product. Additionally, the development of cost-effective and scalable production methods for alternative feeds, alongside strategies to mitigate potential contaminants, will be crucial in making these feeds more viable for widespread adoption.

In conclusion, while the shift toward sustainable feed alternatives is a critical step in addressing the challenges facing global aquaculture, it is clear that achieving a balance between nutritional benefits, environmental sustainability, and food safety requires continued collaboration between researchers, industry stakeholders, and policymakers. With ongoing innovation and careful attention to quality control, alternative feeds can play a significant role in the future of aquaculture, ensuring that farmed seafood continues to provide a nutritious, affordable, and sustainable source of protein for a growing global population.

Conflict of interest: The author declares no conflict of interest.

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