International Journal of Advanced Biochemistry Research 2025; SP-9(2): 505-512

International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
IJABR 2025; SP-9(2): 505-512
www.biochemjournal.com
Received: 11-12-2024
Accepted: 16-01-2025

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Impact of feed additives on the quality of farmed fish

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DOI: https://doi.org/10.33545/26174693.2025.v9.i2Sg.3823

Abstract
The growing demand for high-quality aquaculture products has prompted significant advancements in fish nutrition, with feed additives playing a crucial role. These additives, including probiotics, prebiotics, enzymes, amino acids, and plant-based compounds, improve growth performance, enhance immune responses, and elevate product quality in farmed fish. This review synthesises findings from various studies on the impact of feed additives on growth rate, feed conversion efficiency, health status, and fish meat quality. Probiotics and prebiotics enhance gut health, improving nutrient absorption and disease resistance, while enzymes optimize feed utilisation. Amino acids and vitamins address specific dietary needs, promoting faster growth and higher survival rates. Plant-based additives, such as essential oils and phytobiotics, exhibit antimicrobial and antioxidant properties, benefiting fish health and meat quality. Additionally, feed additives contribute to sustainability by improving feed efficiency and reducing waste outputs. The efficacy of these additives varies depending on factors like fish species, farming conditions, and dosage levels. This review underscores the potential of feed additives in promoting sustainable aquaculture and highlights the need for targeted research to refine formulations for diverse aquaculture systems.

Keywords: Aquaculture nutrition, growth performance, probiotics, plant-based additives, sustainable aquaculture

Introduction

Aquaculture has become a cornerstone in addressing the growing global demand for high-quality and sustainable seafood. As aquaculture continues to evolve, ensuring the health, growth, and product quality of farmed fish is of paramount importance. Among the various strategies developed to enhance aquaculture productivity, feed additives have emerged as essential components of modern fish diets. These additives, though typically added in small quantities, serve significant purposes, including improving feed efficiency, accelerating growth, and safeguarding fish health.

Feed additives are non-nutritive substances designed to complement the nutritional composition of conventional fish feeds. They encompass a diverse range of compounds, such as preservatives, binders, feeding stimulants, probiotics, prebiotics, enzymes, amino acids, and colorants. Each type of additive is formulated to achieve specific goals. For instance, preservatives extend the shelf life of feed (Gómez-Estaca *et al*. 2008) [24]; binders improve feed stability in water (Glencross *et al*. 2010); feeding stimulants enhance palatability and colorants improve the visual appeal of fish products. Probiotics and prebiotics enhance gut health and disease resistance (Balcázar *et al*. 2006) [7], while enzymes optimize nutrient utilization, promoting overall growth efficiency (Francis *et al*. 2001) [17, 18].

The strategic use of feed additives has become critical in advancing sustainable aquaculture practices. By enhancing feed conversion efficiency and reducing waste outputs, additives not only improve productivity but also minimize environmental impacts (Hasan & New 2013) [26]. However, the efficacy of feed additives is influenced by several factors, including fish species, life stage, environmental conditions, and the dosage and combination of additives used. For example, the effectiveness of probiotics varies significantly across species due to differences in gut microbiota composition.

This introduction sets the stage for exploring the multifaceted roles of feed additives in aquaculture, emphasizing their importance in ensuring the sustainable growth, health, and quality of farmed fish.

Growth Performance and Feed Utilization

Feed additives are vital components of modern aquaculture, playing a crucial role in improving farmed fish's growth performance and feed utilization efficiency. These functional additives enhance nutrient absorption, metabolism, and feed conversion, directly influencing key growth metrics such as weight gain, feed conversion ratio (FCR), and specific growth rate (SGR). Additionally, they contribute to sustainable aquaculture practices by reducing feed waste and environmental pollution (Hasan & New 2013; Francis *et al*. 2001) [26, 17, 18].

Probiotics, particularly strains such as *Bacillus subtilis*, *Lactobacillus*, and *Enterococcus*, have proven to be highly beneficial as feed additives in aquaculture. They improve growth performance, feed efficiency, immune responses, and disease resistance in fish. Recent studies have provided a more detailed understanding of their mechanisms and benefits.

Research by Wang *et al*. (2022) [28] demonstrated that dietary supplementation with *Bacillus subtilis* significantly improved the FCR and SGR in Nile tilapia (*Oreochromis niloticus*). These improvements were attributed to enhanced gut health and nutrient digestibility. Zhou *et al*. (2020) [61] observed similar benefits in common carp (*Cyprinus carpio*), where *Bacillus subtilis* enhanced digestive enzyme activity and overall feed utilization efficiency. In large yellow croaker (*Larimichthys crocea*), Xu *et al*. (2020) [63] reported that *Bacillus subtilis* supplementation reduced intestinal inflammation, enhanced intestinal integrity, and improved growth performance. A recent study by Zhang *et al*. (2023) [64] further highlighted that *Bacillus subtilis* improves immune gene expression and boosts resilience against pathogenic infections in various fish species.

Studies on *Lactobacillus* species have shown equally promising results. Ringø *et al*. (2010) [65] emphasized that *Lactobacillus*strains help maintain microbial balance in the gut, leading to better nutrient absorption and growth. Ridha & Azad (2012) [66] observed that *Lactobacillus acidophilus* supplementation significantly improved the growth and survival rates of Nile tilapia under stress conditions. Similarly, Abdel-Tawwab *et al*. (2008) [1] found that *Lactobacillus plantarum* enhanced the immune response and resistance to infections in Nile tilapia. Recent findings by Alam *et al*. (2023) [67] revealed that *Lactobacillus rhamnosus* improved intestinal barrier function and reduced oxidative stress in rainbow trout (*Oncorhynchus mykiss*).

Enterococcus species have also been extensively studied for their probiotic effects. Balcázar *et al*. (2007) [8] reported that *Enterococcus faecium* improved disease resistance against *Lactococcus garvieae* in rainbow trout, along with better growth performance and gut microbiota modulation. In Asian seabass (*Lates calcarifer*), Sharifuzzaman *et al*. (2018) [68] demonstrated that *Enterococcus faecalis* increased mucus secretion and enhanced immunity, leading to improved resistance against pathogenic challenges.

Multispecies probiotics, combining strains like *Bacillus subtilis*, *Lactobacillus acidophilus*, and *Enterococcus faecium*, have shown synergistic benefits in aquaculture. Pirarat *et al*. (2006) [45] reported that such combinations significantly improved growth, FCR, and survival rates in Nile tilapia. Similarly, Jatobá *et al*. (2011) [29] found that multispecies probiotics enhanced resilience against bacterial infections and promoted gut health in Pacific white shrimp (*Litopenaeus vannamei*), suggesting potential applications in fish aquaculture.

Recent studies have continued to support the benefits of probiotics. Zhang *et al*. (2023) [64] found that dietary probiotics increased nutrient digestibility and reduced environmental pollution in aquaculture systems. Similarly, Li *et al*. (2024) [33] emphasized that probiotics improve gut morphology, immune responses, and oxidative stress management, making them integral to sustainable aquaculture practices.

Prebiotics, such as mannan-oligosaccharides (MOS), fructo-oligosaccharides (FOS), and inulin, are non-digestible dietary fibers that selectively stimulate the growth and activity of beneficial gut bacteria, thereby improving feed efficiency, gut health, and overall fish well-being. Numerous studies have highlighted their role in enhancing aquaculture productivity by modulating gut microbiota and boosting immune responses.

Torrecillas *et al*. (2014) [69] demonstrated that dietary supplementation with MOS significantly improved growth performance, feed utilization, and immune status in European sea bass (*Dicentrarchus labrax*). The study found that MOS enhanced the production of antimicrobial compounds and strengthened gut barrier function, resulting in better disease resistance. Similarly, Gómez & Balcázar (2008) [24] reported that the inclusion of FOS and MOS in fish diets promoted the growth of beneficial gut microbiota, improved nutrient absorption, and reduced susceptibility to pathogens. Their findings emphasized the ability of prebiotics to create a gut environment conducive to better health and growth performance.

Recent studies have further supported these benefits. For instance, Safari *et al*. (2020) [70] observed that inulin supplementation in rainbow trout (*Oncorhynchus mykiss*) diets enhanced gut microbial diversity, improved intestinal morphology, and elevated immune parameters such as lysozyme activity and respiratory burst. Furthermore, Khosravi *et al*. (2015) [30] found that MOS supplementation in Pacific white shrimp (*Litopenaeus vannamei*) increased growth performance, feed efficiency, and resistance to *Vibrio* infections, highlighting its applicability in crustacean aquaculture. Another study by Son *et al*. (2023) [71] revealed that prebiotics combined with probiotics (synbiotics) significantly enhanced growth, gut microbiota composition, and survival rates in tilapia (*Oreochromis niloticus*), underscoring the synergistic potential of these dietary additives.

The efficacy of feed additives depends on several factors, including fish species, developmental stage, diet composition, and environmental conditions. For instance, the effectiveness of probiotics varies across species due to differences in gut microbiota composition. Similarly, the optimal dosage and combination of additives must be tailored to specific aquaculture systems to maximize their benefits (Francis *et al*. 2001) [17, 18]. Moreover, environmental factors such as water temperature and pH can influence the activity of enzymes and probiotics, necessitating careful monitoring and adjustment.

Immune Response and Disease Resistance

Functional feed additives play a vital role in enhancing the immune responses of aquatic animals. Research indicates that these additives can improve intestinal health, modulate the intestinal microbiome, and regulate antioxidant stress, thereby increasing disease resistance.

Functional feed additives play a critical role in enhancing aquatic animals' immune responses and disease resistance. Research has demonstrated that certain additives, such as immunostimulants, probiotics, and plant-derived compounds, can improve intestinal health, modulate the intestinal microbiome, and regulate oxidative stress, thereby strengthening the immune system (Balcázar *et al*., 2006) [7]. For example, beta-glucans, a well-known immunostimulant, have been shown to activate innate immune responses in fish by enhancing macrophage and neutrophil activity. Similarly, probiotics like *Lactobacillus* and *Bacillus* species improve gut health and secrete antimicrobial substances that inhibit pathogenic bacteria, reducing the likelihood of infections.

Plant-derived additives, such as essential oils and phytochemicals, also exhibit significant immunomodulatory and antioxidant properties. Compounds like curcumin and thymol have been reported to reduce oxidative stress markers while boosting immune-related gene expression, thereby improving overall disease resilience. Antioxidants, whether naturally derived or synthetic, are pivotal in mitigating oxidative stress caused by intensive farming conditions, further contributing to disease resistance.

Functional feed additives enhance the immune responses of farmed fish and reduce dependency on antibiotics, aligning with global efforts to promote sustainable and antibiotic-free aquaculture practices. However, the effectiveness of these additives depends on factors such as dosage, duration of administration, and compatibility with the fish species and culture system. Continued research into novel and species-specific immunostimulants will be essential to further advance disease management strategies in aquaculture.

Functional feed additives play a critical role in enhancing aquatic animals' immune responses and disease resistance, making them indispensable in modern aquaculture practices. Research has demonstrated that certain additives, including immunostimulants, probiotics, prebiotics, and plant-derived compounds, can significantly improve intestinal health, modulate the intestinal microbiome, and regulate oxidative stress, thereby fortifying the immune system.

Beta-glucans, a widely studied immunostimulant, have shown remarkable potential in boosting the innate immune system. These polysaccharides stimulate the activity of macrophages, neutrophils, and other immune cells, leading to enhanced disease resistance. Reported that beta-glucans improved survival rates in carp (*Cyprinus carpio*) when exposed to *Aeromonas hydrophila*, a common aquaculture pathogen.

Probiotics, such as *Lactobacillus* and *Bacillus* species, contribute to disease resistance by modulating gut microbiota and secreting antimicrobial compounds. Demonstrated that the inclusion of *Bacillus subtilis* in tilapia diets significantly reduced the incidence of bacterial infections by suppressing pathogenic bacteria. Additionally, probiotics enhance digestive enzyme activity, further promoting fish health and resilience.

Prebiotics, such as mannan-oligosaccharides (MOS), provide a favorable substrate for beneficial gut bacteria, promoting intestinal health and immune function. Torrecillas *et al*. (2014) [69] found that MOS supplementation in European sea bass (*Dicentrarchus labrax*) diets improved both immune-related gene expression and resistance to Vibrio infections.

Plant-based additives, including essential oils and phytochemicals, offer immunomodulatory and antioxidant benefits. Compounds such as curcumin (from turmeric) and thymol (from thyme) have demonstrated the ability to reduce oxidative stress markers while enhancing the expression of immune-related genes. These properties are particularly beneficial under intensive farming conditions, where oxidative stress can compromise fish health.

Oxidative stress, a significant concern in aquaculture, is effectively mitigated by antioxidants, which can be either synthetic or naturally derived. Highlighted the role of dietary antioxidants in reducing stress-induced lipid peroxidation, thus improving the overall health and disease resistance of tilapia.

Recent studies have explored the potential of novel additives, such as algal extracts and insect-derived compounds, in enhancing fish immunity. For instance, reported that microalgae-based diets improved immune markers in salmonids, while insect meal-derived immunostimulants have shown promise in promoting gut health and pathogen resistance.

The use of functional feed additives aligns with global efforts to reduce antibiotic reliance in aquaculture, addressing the growing concern over antimicrobial resistance. By naturally enhancing immune defenses, these additives provide a sustainable alternative to antibiotics, supporting disease prevention and control.

The efficacy of functional feed additives depends on several factors, including dosage, duration of administration, fish species, and environmental conditions. For example, Francis *et al*. (2001) [17, 18] emphasized the importance of species-specific formulations to optimize the benefits of immunostimulants. Continued research into novel and species-specific additives is crucial for advancing disease management strategies and ensuring sustainable aquaculture practices.

Functional feed additives represent a powerful tool for enhancing immune responses and disease resistance in aquaculture. By reducing disease outbreaks and minimizing the need for antibiotics, these additives contribute to healthier fish populations and more sustainable farming practices. Future innovations in this field will play a vital role in addressing the challenges posed by intensifying aquaculture systems.

Functional feed additives have proven to be critical in enhancing immune responses and disease resistance in aquaculture species. These additives improve intestinal health, modulate gut microbiota, regulate oxidative stress, and stimulate immune-related pathways, making them indispensable in promoting the health and resilience of farmed fish.

Immunostimulants like beta-glucans are among the most widely studied feed additives. Beta-glucans, derived from yeast, fungi, or algae, are known to activate the innate immune system by stimulating macrophages, neutrophils, and natural killer cells. Demonstrated that beta-glucans enhanced survival rates in common carp (*Cyprinus carpio*) exposed to *Aeromonas hydrophila*, a pathogenic bacterium. Similarly, Sealey *et al*. (2020) [9] reported that dietary beta-glucans improved resistance to bacterial kidney disease in rainbow trout (*Oncorhynchus mykiss*).

Probiotics, including strains of *Lactobacillus*, *Bacillus*, and *Enterococcus*, are essential for maintaining gut health and enhancing immunity. They modulate the intestinal microbiome, produce antimicrobial peptides, and boost the host's immune response. Found that *Bacillus subtilis* supplementation in tilapia (*Oreochromis niloticus*) diets reduced the incidence of bacterial infections by suppressing pathogens like *Streptococcus agalactiae*. Similarly, highlighted the ability of probiotics to enhance gut-associated lymphoid tissue (GALT) activity, further strengthening mucosal immunity in fish.

Prebiotics, such as mannan-oligosaccharides (MOS), fructo-oligosaccharides (FOS), and galacto-oligosaccharides (GOS), provide a substrate for beneficial gut bacteria, promoting microbial balance and enhancing immune function. Torrecillas *et al*. (2014) [69] demonstrated that MOS supplementation improved immune-related gene expression and resistance to *Vibrio harveyi* infections in European sea bass (*Dicentrarchus labrax*). Additionally, Song *et al*. (2018) [62] reported that FOS improved lysozyme activity and immunoglobulin levels in zebrafish (*Danio rerio*), suggesting enhanced systemic immunity.

Plant-based additives, including essential oils, phytochemicals, and herbal extracts, exhibit immunomodulatory, anti-inflammatory, and antioxidant properties. For example, curcumin (from turmeric) and thymol (from thyme) have been shown to reduce oxidative stress markers while upregulating immune-related genes such as interleukin-1β (IL-1β) and tumor necrosis factor-alpha (TNF-α). A study by Harikrishnan *et al*. (2011) [72] demonstrated that dietary garlic (*Allium sativum*) extract improved the immune response and survival rate of olive flounder (*Paralichthys olivaceus*) challenged with *Edwardsiella tarda*.

Oxidative stress caused by intensive aquaculture conditions can compromise fish health, making antioxidants a vital component of functional feeds. These compounds, either synthetic (e.g., butylated hydroxytoluene) or natural (e.g., vitamin C and E), mitigate the damaging effects of reactive oxygen species (ROS). Showed that dietary antioxidants reduced lipid peroxidation and enhanced the overall health of Nile tilapia. Similarly, demonstrated that astaxanthin, a natural carotenoid, significantly improved oxidative stress markers and disease resistance in rainbow trout.

Novel feed additives like algal extracts and insect meals have emerged as promising immunostimulants. Reported that microalgae (*Nannochloropsis*) enhanced immune responses and improved gut health in Atlantic salmon (*Salmo salar*). Additionally, insect-derived compounds, such as chitin and antimicrobial peptides from black soldier fly larvae (*Hermetia illucens*), have shown potential in improving disease resistance and intestinal integrity (Henry *et al*., 2016) [19, 20].

The use of functional feed additives aligns with global efforts to reduce antibiotic use in aquaculture, addressing concerns over antimicrobial resistance (AMR). By naturally enhancing the immune system, these additives reduce the prevalence of diseases and the need for antibiotics. For instance, the supplementation of beta-glucans and probiotics has been shown to effectively control bacterial infections without relying on antibiotics.

The efficacy of functional feed additives depends on multiple factors, including fish species, developmental stage, diet composition, and environmental conditions. Francis *et al*. (2001) [17, 18] emphasized the importance of tailoring formulations to the specific needs of target species to optimize benefits. Moreover, long-term administration and precise dosing strategies are essential to avoid potential over-stimulation of the immune system, which could lead to immune exhaustion or reduced growth performance.

Product Quality and Shelf Life

The incorporation of dietary supplements, such as vitamins E and C, in aquaculture diets has been closely linked to improved product quality and extended shelf life. These vitamins, known for their antioxidant properties, play a crucial role in mitigating oxidative damage to fish flesh, which is a major factor affecting shelf life and marketability. Research has shown that feeding fish, such as southern bluefin tuna (*Thunnus maccoyii*), with diets enriched in vitamins E and C significantly enhances the oxidative stability of their flesh, thereby extending shelf life (Turchini *et al*., 2007) [53]. Elevated levels of these vitamins in fish tissues also contribute to improved texture, color, and flavor, critical parameters influencing consumer acceptance (Sargent *et al*., 2002) [49].

Vitamin E, in particular, acts as a lipid-soluble antioxidant that protects cell membranes from peroxidation, while vitamin C, a water-soluble antioxidant, supports collagen synthesis and prevents oxidative degradation of proteins (Hamre *et al*., 2010) [25]. Together, these vitamins improve both the functional and sensory qualities of fish products. Moreover, the inclusion of other functional additives, such as omega-3 fatty acids and carotenoids, further enhances the nutritional value and visual appeal of fish, meeting consumer demands for healthier and more attractive seafood options (Tocher, 2010) [54].

The use of these additives also aligns with sustainable aquaculture practices by reducing post-harvest losses and improving the economic viability of fish farming operations. However, achieving the desired effects requires precise formulation and appropriate dosage levels tailored to the specific species and farming conditions. Future studies focusing on optimizing the use of antioxidants and other quality-enhancing additives will be instrumental in meeting the growing demand for premium-quality aquaculture products.

The incorporation of dietary supplements, such as vitamins E and C, in aquaculture feeds has been extensively studied for their ability to improve product quality and extend shelf life. These antioxidants play a pivotal role in preventing oxidative damage to fish flesh, which is a major factor influencing shelf life, nutritional quality, and consumer acceptance.

Vitamin E, a lipid-soluble antioxidant, protects cellular membranes from lipid peroxidation by neutralizing free radicals. This protection preserves the structural integrity of fish tissues and prevents rancidity, a common issue in fatty fish. Vitamin C, a water-soluble antioxidant, complements vitamin E by regenerating its active form while also supporting collagen synthesis, which is essential for maintaining tissue firmness (Hamre *et al*., 2010) [25].

Research by Turchini *et al*. (2007) [53] demonstrated that southern bluefin tuna (*Thunnus maccoyii*) fed diets enriched with vitamins E and C exhibited significantly higher oxidative stability in their flesh, resulting in an extended shelf life during refrigerated storage. Similarly, a study by Rodrigues *et al*. (2014) [47] on Nile tilapia (*Oreochromis* *niloticus*) revealed that supplementation with vitamin C improved flesh firmness and reduced lipid peroxidation, thereby enhancing sensory attributes such as taste and texture.

The inclusion of omega-3 fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), in aquafeeds further contributes to product quality. Omega-3 fatty acids enhance the nutritional profile of fish, aligning with consumer demand for healthier seafood options. Additionally, studies have shown that diets rich in omega-3s improve the oxidative stability of fish products, reducing off-flavors and maintaining freshness during storage (Tocher, 2010; Glencross *et al*., 2020) [54, 23].

Carotenoids, such as astaxanthin and canthaxanthin, are essential for improving the visual appeal of fish, particularly in species like salmonids, where pigmentation is a key quality criterion. Torrissen *et al*. (1995) [52] highlighted that dietary astaxanthin not only enhances pigmentation but also acts as a potent antioxidant, reducing oxidative stress in fish tissues. Recent studies, such as those by Choubert *et al*. (2009) [14], have confirmed that carotenoids improve the aesthetic and nutritional value of fish, increasing their marketability.

Beyond vitamins and carotenoids, other additives like selenium, polyphenols, and natural antioxidants have shown promise in enhancing product quality. Selenium, an essential trace element, plays a role in reducing lipid oxidation and improving the oxidative stability of fish flesh (Rider *et al*., 2009) [48]. Polyphenols derived from plant extracts, such as rosemary and green tea, have been investigated for their antioxidant properties. Studies by Kumar *et al*. (2015) [73] demonstrated that polyphenol supplementation significantly delayed lipid oxidation in common carp (*Cyprinus carpio*), enhancing both shelf life and sensory attributes.

The inclusion of these functional additives directly impacts key parameters that influence consumer preferences, such as texture, flavor, and color. Sargent *et al*. (2002) [49] emphasized that elevated levels of vitamins and omega-3 fatty acids in fish tissues improve not only sensory qualities but also the nutritional value of aquaculture products.

From an economic perspective, enhancing product quality and shelf life reduces post-harvest losses, improving profitability for aquaculture operations. This aligns with sustainable aquaculture practices by minimizing waste and ensuring efficient use of resources. Furthermore, the use of natural and functional additives supports the production of premium-quality seafood that meets evolving consumer expectations for sustainability and healthfulness.

Despite significant advancements, further research is needed to optimize the use of these additives. Factors such as species-specific requirements, farming conditions, and optimal dosage levels need to be thoroughly investigated. Future studies should also explore emerging additives, such as microalgae-derived antioxidants and insect-based carotenoids, to diversify the portfolio of quality-enhancing supplements in aquaculture

Environmental Considerations

The sustainability of feed additives is crucial for reducing the ecological footprint of aquaculture and ensuring the industry's long-term viability. The traditional reliance on fishmeal and fish oil has raised significant concerns about overfishing, resource depletion, and environmental impacts. Consequently, alternative feed formulations using plant-based ingredients, insect meals, algae, and processed animal proteins have been extensively explored to address these challenges.

Plant-derived ingredients, such as soybean meal, rapeseed, sunflower by-products, and lupins, are widely recognized as sustainable alternatives to fishmeal. These ingredients reduce dependence on marine resources and lower the carbon footprint of feed production (Tacon & Metian, 2008). However, plant-based feeds often contain anti-nutritional factors (ANFs), such as tannins, phytates, and lectins, which can impair nutrient absorption and fish health. To mitigate these limitations, enzyme supplementation—such as phytase to degrade phytates—and fermentation processes have been employed. Studies, including Francis *et al*. (2001) [17, 18] and Zhou *et al*. (2018) [62], have demonstrated that these approaches improve the nutritional value of plant-based feeds. For instance, Drew *et al*. (2007) found that fermented soybean meal significantly enhanced growth performance and feed utilization in rainbow trout (*Oncorhynchus mykiss*). Furthermore, sustainable farming practices, such as intercropping and minimizing agrochemical use, can further reduce the environmental impact of plant-derived ingredients (Gatlin *et al*., 2007) [21].

Insect meals, particularly from black soldier fly larvae (*Hermetia illucens*) and mealworms (*Tenebrio molitor*), are emerging as novel and sustainable protein sources. These insects efficiently convert organic waste into high-quality protein while requiring minimal land and water resources (Henry *et al*., 2016) [19, 20].

Research by Gasco *et al*. (2016) revealed that black soldier fly meal could replace up to 50% of fishmeal in European sea bass (*Dicentrarchus labrax*) diets without affecting growth performance or feed efficiency. Additionally, Nogales-Mérida *et al*. (2019) [41] demonstrated that insect meal inclusion improved gut health and immune responses in tilapia (*Oreochromis niloticus*), showcasing its potential to enhance fish health alongside sustainability.

Algae, both microalgae and macroalgae, are promising feed components due to their high nutritional value and environmental benefits. Microalgae such as *Chlorella*, *Nannochloropsis*, and *Spirulina* are rich in essential fatty acids (e.g., omega-3s), proteins, vitamins, and pigments, making them valuable inclusions in aquafeeds (Spolaore *et al*., 2006; Barrows *et al*., 2020) [15, 9].

A study by Kiron *et al*. (2012) [31] found that supplementing diets with microalgae improved the growth performance and immune status of Atlantic salmon (*Salmo salar*). Algae cultivation also provides environmental advantages, such as carbon sequestration and wastewater bioremediation, without competing for arable land or freshwater resources (Bleakley & Hayes, 2017) [11]. Recent advancements in algae bioprocessing, including heterotrophic cultivation methods, have further improved the scalability and cost-effectiveness of algae-based feeds (Liang *et al*., 2021).

Processed animal proteins, derived from non-ruminant by-products such as poultry, offer a circular economy solution in aquaculture. These proteins are rich in essential amino acids and can effectively replace fishmeal in aquafeeds (Nunes *et al*., 2014) [40].

Conducted a meta-analysis demonstrating that including poultry by-product meal in diets for carnivorous species like Atlantic salmon and trout improved growth performance. Monteiro *et al*. (2018) [38] highlighted that utilizing PAPs contributes to waste valorization, reducing the environmental burden associated with animal by-product disposal.

Emerging technologies, such as precision fermentation and biotechnology, hold promise for optimizing feed formulations. Single-cell proteins derived from bacteria, yeast, and fungi have shown potential as scalable and sustainable protein sources for aquaculture (Øverland *et al*., 2010) [42]. Recent studies, such as those by Pacheco *et al*. (2021) [43], are exploring how these technologies can be integrated into commercial production systems.

Life cycle assessments (LCAs) are increasingly employed to evaluate the environmental impacts of feed ingredients. Pelletier & Tyedmers (2007) [44] emphasized the importance of LCAs in identifying improvement areas and ensuring the sustainability of aquaculture practices. Moreover, innovations like precision feeding technologies can further enhance feed utilization efficiency, minimizing waste and environmental impacts (Ytrestøyl *et al*., 2015) [55].

Conclusion

Incorporating appropriate feed additives into aquaculture diets can significantly improve the growth performance, health status, and product quality of farmed fish. Ongoing research and development of sustainable feed additives are essential to meeting the growing demands of the aquaculture industry while minimizing environmental impacts.

Integrating feed additives into aquaculture practices has proven to be a transformative strategy for enhancing the growth, health, and product quality of farmed fish while addressing sustainability challenges. Feed additives such as probiotics, enzymes, antioxidants, and alternative protein sources contribute to improved feed efficiency, immune function, and shelf life, thereby ensuring the competitiveness and profitability of aquaculture operations.

Moreover, the adoption of sustainable feed formulations using novel ingredients like insect meals, algae, and plant by-products plays a crucial role in reducing the environmental footprint of the aquaculture industry. These alternatives not only decrease the reliance on traditional fishmeal and fish oil but also align with global efforts to promote resource efficiency and mitigate climate change impacts.

However, the successful application of feed additives requires careful consideration of species-specific needs, environmental conditions, and precise dosing to achieve optimal results. Collaborative efforts among researchers, industry stakeholders, and policymakers will be essential to advance the development and implementation of innovative feed technologies.

Looking ahead, continued research into novel additives, sustainable formulations, and their long-term impacts on aquaculture systems will be critical for meeting the growing global demand for seafood. By balancing productivity with environmental stewardship, feed additives offer a pathway toward a more sustainable and resilient aquaculture industry.

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