Animal Health Research Journal

P-ISSN : 2356-7767 On Line-ISSN : 2535-1524
Journal Homepage: https://animalhealth.ahri.gov.eg/ Review Article

Fish Feed Additives in Aquaculture: Advancing Nutrition, Immunity, and Sustainability

Nagwa, I.S. Abu-Zahra*; Shireen, Soliman; Amany, M. Ghoniem** and Mona, E. Abass****

*Fish Diseases Unit, Kafrelsheikh Provincial Lab, Animal Health Research Institute (AHRI), Agriculture Research Center (ARC), Giza, Egypt
**Biochemistry Unit, Kafrelsheikh Provincial Lab, Animal Health Research Institute (AHRI), Agricultural Research Center (ARC), Giza, Egypt

Received in 30/3/2025
Received in revised from 28/4/2025
Accepted in 17/6/2025

Keywords:
Aquaculture Nutrition,
Phytogenics,
Immunostimulants,
Oxidative Stress,
Fish Health,
Sustainable Aquaculture

Abstract

The rapid expansion of aquaculture as a key contributor to global food security has underscored the importance of efficient and sustainable nutrition strategies. In this context, fish feed additives have emerged as critical components in modern aquafeeds, aimed at enhancing growth performance, feed efficiency, health status, and environmental resilience of cultured species. This review provides a comprehensive overview of various feed additives, including phytogenics, probiotics, prebiotics, organic acids, enzymes, and immunostimulants, highlighting their mechanisms of action and functional roles. Emphasis is placed on their potential to improve digestion, boost immune responses, mitigate oxidative stress, enhance resistance to pathogens, and support overall fish welfare. The increasing demand for alternatives to antibiotic growth promoters and conventional feed ingredients has accelerated the development of natural, bioactive, and eco-friendly additives. Furthermore, the review explores recent advances, comparative effectiveness, and the integration of these additives in aquaculture nutrition under intensive and stress-prone farming systems. Current challenges, knowledge gaps, and future research directions are also discussed to guide the sustainable application of feed additives in aquaculture.

Corresponding author: Nagwa, I.S. Abu-Zahra, Fish Diseases Unit, Kafrelsheikh Provincial Lab, Animal Health Research Institute (AHRI) Dokki, Giza Agriculture Research Center (ARC), Nadi El-Seid Street, Dokki P.O., Giza 12618, Egypt.
Email address: nagwaabuzahra09@gmail.com

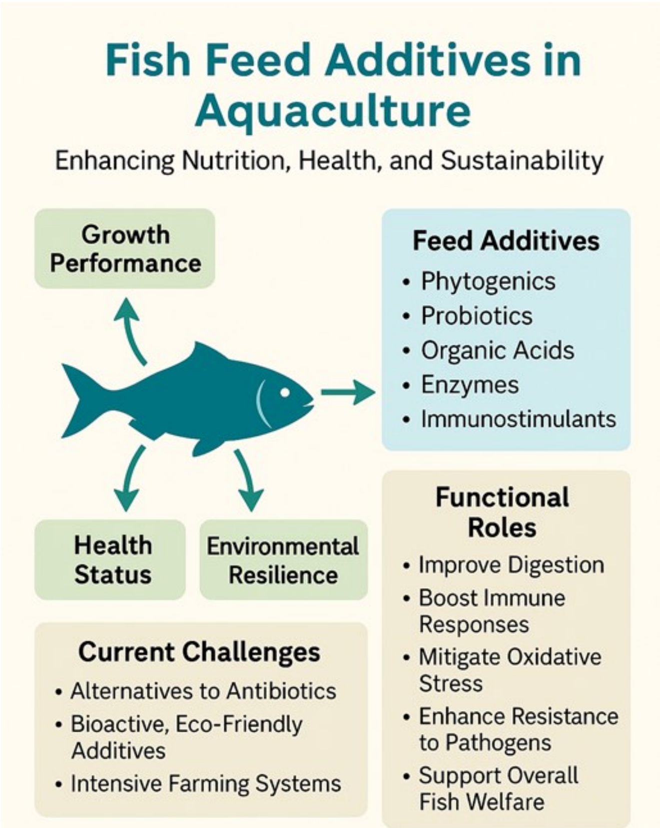

Figure (1). Graphical abstract showing the role of fish feed additives in sustainable aquaculture. The infographic illustrates the contribution of various fish feed additives, including phytogenics, probiotics, prebiotics, organic acids, enzymes, and immunostimulants, to enhanced growth performance, feed efficiency, health status, and environmental resilience. It highlights their functional roles in digestion improvement, immune response boosting, oxidative stress mitigation, pathogen resistance, and welfare support, while also emphasizing current challenges and research directions for sustainable aquaculture practices. The graphical abstract was created by the author using original illustrations. No external sources or copyrighted materials were used.

1. Introduction

Aquaculture has emerged as one of the fastest-growing sectors in global food production, playing a crucial role in meeting the rising demand for high-quality animal protein (FAO, 2022). As capture fisheries approach their sustainable limits, aquaculture continues to expand, contributing significantly to the global seafood supply. This rapid growth has intensified the focus on efficiency, sustainability, and health management within aquaculture systems, with nutrition recognized as a fundamental pillar for achieving optimal fish performance and production outcomes **(Gatlin *et al.,* 2007).**

Traditionally, fish diets have relied heavily on fishmeal and fish oil as primary nutrient sources. However, growing concerns regarding the sustainability, availability, and cost of these conventional ingredients have prompted the search for alternative feed components **(Naylor *et al.,* 2021).** In this context, the development and application of functional feed additives have gained considerable interest. These additives not only enhance growth performance and feed efficiency but also promote fish health, improve disease resistance, strengthen immune responses, and mitigate the negative impacts of environmental stressors **(Ringø *et al.,* 2018).** Moreover, as the industry shifts towards reduced antibiotic usage, natural and bioactive compounds, such as phytogenics, probiotics, prebiotics, and organic acids, are increasingly incorporated into aquafeeds as sustainable solutions for maintaining fish welfare **(Van Doan *et al.,* 2020).**

The growing demand for eco-friendly, effective, and multifunctional feed additives is further driven by the challenges of intensified farming conditions, frequent disease outbreaks, and the need for improved product quality. Functional additives offer promising strategies to enhance physiological functions, antioxidant capacity, nutrient utilization, and water quality, critical factors that align with the objectives of sustainable aquaculture **(Ahmed *et al.*, 2022).**

The objectives of this review are to:

i. Provide a comprehensive overview of the feed additives types used in aquaculture.
ii. evaluate their functional roles in promoting fish growth, health, and environmental resilience.
iii. Highlight recent advances and mechanisms of action.
iv. Discuss future directions and research gaps related to the application of feed additives in modern aquaculture practices.

2. Classification of Fish Feed Additives

Fish feed additives are non-nutritive substances incorporated into aquafeeds to promote growth, health, feed utilization, and resistance to stress and disease. Based on their origin and functional roles, fish feed additives can be classified into the following categories (Figure 2):

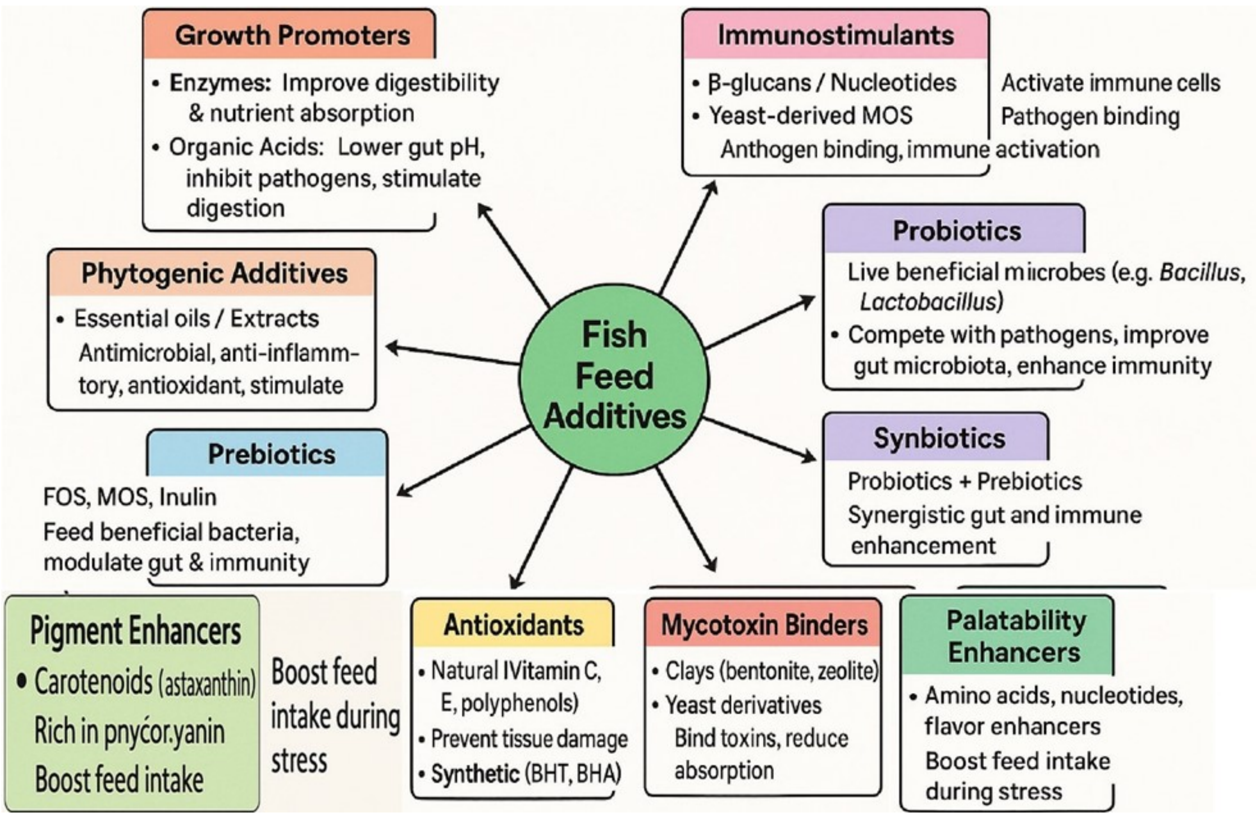

Figure (2). Schematic representation of the classification and mechanisms of fish feed additives. The diagram highlights ten major categories: growth promoters, immunostimulants, phytogenic additives, probiotics, prebiotics, synbiotics, antioxidants, mycotoxin binders, pigment enhancers, and palatability enhancers, each contributing to fish health, nutrition, and disease resistance. The figure was created by the author using original illustrations. No external sources or copyrighted materials were used.

2. 1. Growth Promoters
These compounds enhance growth performance and feed efficiency by improving digestion and nutrient absorption. Examples include:
- Enzymes (e.g., protease, phytase) improve nutrient availability and digestibility **(Adeoye *et al.,* 2016).**
- Organic acids lower gastrointestinal pH, inhibit pathogenic bacteria and stimulate digestive enzyme secretion **(Ng & Koh, 2017).**

2.2. Immunostimulants
These are compounds that enhance the non-specific immune responses of fish, improving resistance to pathogens. Common examples include:
- β-glucans, peptidoglycans, and nucleotides from microbial or yeast sources **(Bricknell & Dalmo, 2005).**
- Yeast cell wall components, such as mannan-oligosaccharides, act as pathogen-binding agents and immune enhancers **(Ringø *et al.,* 2010).**

2.3. Phytogenic Additives (Phytobiotics)
Derived from plants (herbs, spices, essential oils, or extracts), phytogenics possess antimicrobial, antioxidant, anti-inflammatory, and appetite-stimulating properties **(Reverter *et al.,* 2014; Abu-Zahra *et al.,* 2024; 2025).** Their growing popularity is attributed to their natural origin and multifunctional benefits.

2.4. Probiotics
Live microorganisms colonize the gut and confer health benefits such as improved digestion, competitive exclusion of pathogens, and enhanced immunity **(Merrifield *et al.,* 2010).** Common genera include *Bacillus*, *Lactobacillus*, *Enterococcus*, and *Saccharomyces*.

2.5. Prebiotics
Non-digestible feed ingredients that selectively stimulate beneficial gut microbiota. Examples include:
- Fructo-oligosaccharides (FOS)
- Mannan-oligosaccharides (MOS)
- Inulin

  These compounds enhance gut health and modulate immune responses **(Ringø *et al.,* 2010).**

2.6. Synbiotics
These are synergistic combinations of probiotics and prebiotics aimed at enhancing the survival and implantation of beneficial microbes in the gastrointestinal tract **(Hai, 2015).**

2.7. Antioxidants
Antioxidants prevent oxidative damage in fish tissues and preserve feed quality. They can be:
- Natural antioxidants, such as vitamins C and E or polyphenols from plants **(Abdel-Tawwab *et al.,* 2020a)**
- Synthetic antioxidants like butylated hydroxytoluene (BHT) and butylated hydroxyanisole (BHA) (use limited due to regulatory concerns)

2.8. Mycotoxin Binders
These compounds reduce the bioavailability of mycotoxins in feed. Common types include:
Clay minerals (e.g., bentonite, zeolite)
Yeast derivatives, especially glucomannans **(Manning *et al.,* 2005)**

2.9. Pigment Enhancers
Used primarily in ornamental and market fish to enhance coloration. These include:
Carotenoids, such as astaxanthin and canthaxanthin
Spirulina is rich in phycocyanin and carotenoids **(Gouveia *et al.,* 2003)**

2.10. Palatability Enhancers
Additives like free amino acids (e.g., glycine, alanine), nucleotides, and flavor enhancers are used to increase feed intake, especially under stressful or suboptimal conditions **(Hernández *et al.,* 2008).**

3. Functional Benefits of Feed Additives
3.1. Growth Performance
Feed additives have been widely documented to significantly improve growth performance parameters, such as feed conversion ratio (FCR), weight gain (WG), and specific growth rate (SGR) in various fish species. Additives including probiotics, phytogenics, and organic acids have been particularly effective, primarily by enhancing nutrient absorption and improving digestive efficiency. Probiotics help in maintaining a healthy gut microbiota, leading to better feed utilization and growth **(Ringø *et***

***al.,* 2010).** Similarly, phytogenics, derived from plant-based compounds, have been shown to stimulate digestive secretions and possess antimicrobial properties that contribute to enhanced nutrient availability and utilization **(Dawood & Koshio, 2016; Abu-Zahra *et al.,* 2024).** Organic acids also play a critical role by modulating intestinal pH and improving mineral absorption, thereby supporting better growth performance. The cumulative effect of these additives ultimately results in more efficient feed use, higher weight gain, and improved overall health and productivity of cultured fish.

3.2. Immune Modulation

Several feed additives can modulate the fish immune system by upregulating immune-related gene expression, increasing lysozyme activity, and elevating leukocyte counts. Immunostimulants such as β-glucans and nucleotides are particularly effective in enhancing both innate and adaptive immune responses **(Bagni *et al.,* 2005; Zheng *et al.,* 2021).** β-glucans, derived mainly from yeast cell walls, are known to activate macrophages and other immune cells, leading to a more robust defense against pathogens. Similarly, dietary nucleotides can enhance lymphocyte proliferation and antibody production, strengthening adaptive immunity.

Recent studies have further highlighted the role of natural compounds in immunomodulation. For instance, **Abu-Zahra *et al.* (2023)** demonstrated that ascorbic acid supplementation significantly mitigated the immunosuppressive effects and DNA damage in *Oreochromis niloticus* exposed to oxytetracycline, supporting the use of antioxidants as immune boosters. Additionally, the use of *Mentha piperita* powder in the diet of *O. niloticus* enhanced not only growth performance but also disease resistance and immune parameters when challenged with *Vibrio alginolyticus* **(Abu-Zahra *et al.,* 2024)**. Moreover, dietary supplementation with *Pelargonium sidoides* extracts has been shown to alleviate thermal stress-induced immunosuppression in *O. niloticus*, as evidenced by improved physiological and immunological indicators **(Abu-Zahra *et al.,* 2025).** These findings underscore the potential of natural feed additives in enhancing fish immunity and promoting better health outcomes under both infectious and environmental stress conditions.

3.3. Oxidative Stress Management

Feed additives, including vitamins C and E, polyphenols, and herbal extracts, have been shown to significantly contribute to oxidative stress management in fish by enhancing the activities of key antioxidant enzymes. These additives bolster the biological defense system by increasing the activities of superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx), which are critical for neutralizing reactive oxygen species and protecting tissues from oxidative damage **(Hoseinifar *et al.,* 2017; Giri *et al.,* 2019).**
Vitamins C and E are well-recognized for their potent antioxidant properties, where vitamin C functions by scavenging free radicals and regenerating other antioxidants, while vitamin E protects cellular membranes from lipid peroxidation. Similarly, polyphenolic compounds and herbal extracts serve as natural sources of antioxidants, further strengthening cellular defense mechanisms.

Recent studies emphasize that supplementation with antioxidant-rich compounds not only mitigates oxidative stress but also enhances overall health, growth performance, and immune function in cultured fish species. For instance, **Abu-Zahra *et al.* (2023)** demonstrated that ascorbic acid (vitamin C) supplementation significantly reduced oxidative DNA damage and improved antioxidant status in *Oreochromis niloticus* exposed to oxytetracycline. Likewise, **Abu-Zahra *et al.* (2025)** reported that dietary supplementation with *Pelargonium sidoides* extracts enhanced the antioxidant defense system in *O. niloticus* under thermal stress, as evidenced by elevated SOD, CAT, and GPx activities. Additionally, herbal additives such as *Mentha piperita* powder have been shown to boost antioxidant capacity, improving fish resilience against bacterial infections like *Vibrio alginolyticus* **(Abu-Zahra *et al.,* 2024).** These findings collectively reinforce the beneficial role of natural feed additives in enhancing oxidative stress management, thereby promoting better health, disease resistance, and survival rates in aquaculture.

3.4. Disease Resistance

Dietary supplementation with immunostimulants, probiotics, and phytogenics has been widely reported to increase disease resistance in fish against a range of pathogens such as *Aeromonas hydrophila*, *Vibrio* spp., and *Saprolegnia* spp. These feed additives enhance the fish's immune barriers by stimulating both innate and adaptive immune responses, improving mucosal defenses, and boosting pathogen clearance capabilities **(Harikrishnan *et al.,* 2011; Dawood *et al.,* 2021).**

Probiotics have been shown to competitively exclude pathogenic bacteria from colonizing the gastrointestinal tract, while immunostimulants like β-glucans enhance phagocytic activity and production of antimicrobial compounds. Phytogenic additives, derived from medicinal plants, not only modulate immune-related gene expression but also possess direct antimicrobial properties.

Recent research has further validated the effectiveness of natural phytogenics in enhancing disease resistance. **Abu-Zahra *et al.* (2024)** demonstrated that dietary inclusion of *Mentha piperita* powder significantly improved survival rates and resistance of *Oreochromis niloticus* against *Vibrio alginolyticus* infection. Similarly, **Abu-Zahra *et al.* (2025)** reported that supplementation with *Pelargonium sidoides* extract helped fish better cope with stress conditions while maintaining strong resistance against opportunistic pathogens. These studies highlight the promising role of dietary strategies in reducing disease outbreaks in aquaculture while minimizing reliance on antibiotics.

3.5. Stress Tolerance

Feed additives play a vital role in enhancing fish stress tolerance by modulating physiological responses and improving survival rates under various environmental stressors, including temperature fluctuations, salinity changes, and handling stress. Supplementation with specific additives has been shown to reduce plasma cortisol levels, stabilize metabolic functions, and support antioxidant defenses, thus mitigating the detrimental effects of stress **(Silva *et al.,* 2015; Abdel-Tawwab *et al.,* 2020b).**

Adaptogenic additives, including herbal extracts, vitamins, and probiotics, play a vital role in enhancing stress resilience and maintaining immune competence under adverse conditions. Recent studies support this approach; for instance, **Abu-Zahra *et al.* (2025)** reported that dietary supplementation with *Pelargonium sidoides* extract effectively mitigated thermal stress in *Oreochromis niloticus* by enhancing antioxidant enzyme activities and improving immune parameters. Such nutritional strategies are increasingly essential for sustaining fish health and productivity in aquaculture systems exposed to variable and challenging environmental conditions.

3.6. Antibiotic Alternatives

As concerns about antimicrobial resistance rise, the demand for alternatives to antibiotics in aquaculture is growing. Many feed additives, such as probiotics, prebiotics, and immunostimulants, can help reduce the reliance on antibiotics by boosting the fish's natural defenses and maintaining gut health. Research into effective, sustainable alternatives that reduce disease susceptibility while minimizing the use of antibiotics will be crucial for both fish health and regulatory compliance. The strategic use of these natural alternatives supports environmentally responsible aquaculture practices and ensures the production of safe seafood products for human consumption. The documented effects of various feed additives on fish health and performance are summarized in Table 1.

Table 1. Documented Effects of Feed Additives on Fish Health and Performance

Additive	Growth Performance	Immune Response	Disease Resistance	References
Probiotics	↑ Weight gain, ↓ FCR	↑ Lysozyme activity, ↑ phagocytosis	↑ Resistance to *Aeromonas hydrophila*, *Vibrio* spp.	**Wang *et al.* (2023); Dawood *et al.* (2021)**
Prebiotics	Moderate growth improvement	↑ Cytokine expression, gut microbiota balance	↑ Resistance to bacterial infections	**Akrami *et al.* (2022)**
Phytogenics	↑ Growth rate, ↑ feed intake	↑ Antioxidant enzymes (SOD, CAT, GPx), ↓ cortisol	↓ Mortality under stress and infection	**Reverter *et al.* (2014); Abu-Zahra *et al.* (2024; 2025)**
Organic Acids	↓ FCR, ↑ digestibility	Mild immune enhancement	↓ Gut bacterial load	**Abou-Elgheit *et al.* (2022)**
Enzymes	↑ Growth, improved nutrient absorption	Indirect support via better nutrition	Enhanced resilience to pathogens	**Maas *et al.* (2020)**
Immunostimulants	Variable growth effects	↑ IgM, complement activity, ↑ leukocyte count	↑ Survival after pathogen challenges	**Yousefi *et al.* (2023); Bagni *et al.* (2005)**
Nanoparticles	↑ Growth performance, ↑ nutrient retention	↑ Antioxidant enzymes, ↓ oxidative stress	↑ Resistance to bacterial infection	**Hasan *et al.* (2024)**
Vitamins and Herbal Extracts	↑ Growth under stress conditions	↑ Antioxidant defense (SOD, CAT, GPx), ↓ cortisol	↑ Survival under thermal and bacterial stress	**Abu-Zahra *et al.* (2023; 2024; 2025)**

Data presented in this table are compiled from peer-reviewed scientific literature.

4. Mechanisms of Action of Feed Additives

Feed additives exert their beneficial effects through diverse biological mechanisms that influence digestion, immune modulation, microbial balance, and stress physiology in aquaculture species. Understanding these mechanisms helps optimize additive selection for specific production goals.

4.1. Modulation of Gut Microbiota

Probiotics and prebiotics modulate the gut microbiome by enhancing the proliferation of beneficial bacteria such as *Lactobacillus* and *Bacillus* spp., while suppressing opportunistic pathogens. This microbial shift leads to improved intestinal integrity and nutrient utilization, as well as enhanced mucosal immunity **(Ringø *et al.,* 2010; Dawood *et al.,* 2019).**

4.2. Enhancement of Digestive Enzyme Activity

Feed additives such as enzymes (e.g., protease, amylase, phytase) and phytogenics stimulate the activity of endogenous digestive enzymes, leading to better feed conversion efficiency and growth performance. Organic acids also reduce gut pH, optimizing enzyme activity and nutrient solubility **(Adeoye *et al.,* 2016; Citarasu, 2010).**

4.3. Immunostimulation

Immunostimulants like β-glucans, nucleotides, and yeast cell wall derivatives enhance both innate and adaptive immune responses by activating phagocytic cells, increasing lysozyme activity, and modulating cytokine expression. These effects improve the fish's ability to resist infectious diseases **(Bagni *et al.,* 2005; Harikrishnan *et al.,* 2011).**

4.4. Antioxidant Defense

Many additives, particularly vitamins (C, E), polyphenols, and herbal extracts, exhibit antioxidant properties that scavenge reactive oxygen species (ROS) and enhance the activities of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx). This mechanism helps maintain cellular homeostasis under stressful conditions **(Giri *et al.,* 2019; Hoseinifar *et al.,* 2017; Abu-Zahra *et al.,* 2023).**

4.5. Pathogen Inhibition and Toxin Binding

Some additives act directly against pathogens or their toxins. For instance, phytogenic compounds and essential oils possess antimicrobial properties that disrupt bacterial cell membranes. Meanwhile, mycotoxin binders like bentonite and yeast cell wall components adsorb harmful compounds in the gut, preventing systemic toxicity **(Santacroce *et al.,* 2021; Manafi *et al.,* 2022).**

4.6. Appetite Stimulation and Palatability

Flavor enhancers, amino acids, and nucleotides included as palatability enhancers improve feed intake, especially under stress or during disease recovery. This ensures sustained nutrient intake critical for immunity and growth **(Abdel-Tawwab *et al.,* 2020b).**

5. Comparative Effectiveness and Application Strategies

5.1. Comparative Effectiveness

The effectiveness of feed additives in aquaculture depends largely on the species, dosage, and specific aquaculture conditions under which they are applied. Comparative studies highlight how targeted application strategies can maximize their biological benefits while maintaining cost-efficiency.

For instance, dietary inclusion of garlic extracts at levels of 1–2% in *Oreochromis niloticus* has been associated with improved immune responses, reduced feed conversion ratio (FCR), and overall better growth performance **(Awad & Awaad, 2017).** Garlic's bioactive compounds, such as allicin, enhance both digestive and immunological functions, making it a popular phytogenic additive in tilapia farming.

Similarly, supplementation with β-glucans at concentrations ranging from 0.1% to 0.5% has shown remarkable immunomodulatory effects in *Cyprinus carpio*, specifically by elevating lysozyme activity and enhancing innate immune responses **(Harikrishnan *et al.,* 2011).** β-glucans are recognized as potent immunostimulants, often applied during periods of stress or heightened disease risk.

The use of the phytase enzyme in *Pangasianodon hypophthalmus* diets at doses between 500 and 1000 U/kg improves phosphorus digestibility, leading to enhanced growth performance and better nutrient utilization **(Maas *et al.,* 2020).** This approach not only benefits fish health but also supports environmental sustainability by reducing phosphorus waste in aquaculture effluents.

Furthermore, supplementation with organic acids such as formic and lactic acid at a dose of 0.5–1.5% in *Labeo rohita* has been reported to lower gut pH, inhibit pathogenic bacteria, and promote a healthier intestinal microbiota **(Sidiq *et al.,* 2023).** These benefits translate into improved disease resistance and better feed efficiency.

In practice, optimal results require species-specific customization of additive types and dosages, careful monitoring of physiological responses, and adjustment based on production goals (e.g., growth, health, stress tolerance). Combining multiple additives, such as phytogenics with probiotics or organic acids, is emerging as a promising strategy to achieve synergistic effects, enhance resilience, and minimize reliance on antibiotics in aquaculture systems. Comparative effectiveness and application strategies of different feed additives across aquaculture species are summarized in Table 2.

5.2. Synergistic Effects of Additive Combinations

Many feed additives exhibit enhanced efficacy when combined with other supplements, creating synergistic effects. For example, probiotics may work better when combined with prebiotics, enhancing gut health and immune responses. Similarly, phytogenics combined with organic acids can improve nutrient digestibility and pathogen resistance. Research into optimal additive combinations could lead to more effective and cost-efficient feed formulations, enhancing overall fish health and performance. The integration of synergistic strategies represents a promising area for innovation in feed additive application.

Table (2). Comparative Effectiveness and Application Strategies of Different Feed Additives in Fish

Additive	Target Species	Dose Range	Documented Outcomes	Reference
Garlic extract	*Oreochromis niloticus*	1–2%	Improved immunity, reduced FCR	**Awad & Awaad (2017)**
β-glucans	*Cyprinus carpio*	0.1–0.5%	Increased lysozyme activity, enhanced immune defense	**Harikrishnan *et al.* (2011)**
Phytase enzyme	*O. niloticus*	500–1000 U/kg	Enhanced phosphorus digestibility, improved growth	**Maas *et al.* (2020)**
Organic acids	*Labeo rohita*	0.5–1.5%	Lowered gut pH, inhibition of pathogenic bacteria	**Sidiq *et al.* (2023)**

Data presented in this table are compiled from peer-reviewed scientific literature. FCR = Feed Conversion Ratio; U/kg = Units per kilogram of feed.

6. Key Challenges and Research Directions for Feed Additives

Despite the significant advancements in the development and application of feed additives in aquaculture, several challenges continue to hinder their widespread adoption and consistent success. High production costs, particularly for specialized additives such as enzymes and nanoparticles, limit their affordability and scalability for commercial fish farming operations. Additionally, the efficacy of many feed additives remains inconsistent across different fish species, developmental stages, and environmental conditions, emphasizing the need for species-specific formulations and synergistic strategies. Regulatory frameworks governing the approval and usage of feed additives are often fragmented or underdeveloped, leading to uncertainties in product safety and market acceptance. Furthermore, the physical and chemical stability of additives during feed manufacturing processes, such as pelleting and extrusion, poses a technical barrier that may compromise their bioactivity. Finally, consumer perceptions, especially regarding the use of "unnatural" or nanotechnology-based ingredients, can influence market demand and acceptance. Addressing these challenges through strategic innovations and harmonized regulations is crucial for optimizing the role of feed additives in promoting sustainable aquaculture. These key challenges and potential research directions are summarized in Table 3.

6.1. Dose Standardization

A major challenge in the application of feed additives is the lack of dose standardization across different fish species and production systems. Optimal dosages often vary depending on species, developmental stage, environmental conditions, and the specific additive used **(Reverter *et al.,* 2014; Dawood *et al.,* 2020).** Without well-defined dose–response studies, there is a risk of underdosing, which may result in limited efficacy, or overdosing, which could cause adverse effects on fish health and lead to economic inefficiency **(Van Doan *et al.,* 2021).** Future research must prioritize establishing precise, species-specific dosing guidelines to maximize the benefits of feed additives while minimizing potential risks.

6.2. Species-Specific Responses

Fish species exhibit considerable variability in their physiological responses to dietary feed additives. An additive that enhances growth performance or immune function in one species may have minimal or even adverse effects in another **(Ringø *et al.,* 2018; Dawood *et al.,* 2019).** These interspecific differences are largely influenced by genetic, metabolic, digestive, and immunological factors **(Merrifield *et al.,* 2010).** Therefore, it is crucial to conduct species-specific evaluations and tailor additive formulations to the unique nutritional and physiological requirements of each cultured species to achieve optimal outcomes **(Kiron, 2012).**

6.3. Environmental Impacts

While feed additives offer numerous health and performance benefits, their potential environmental impacts must be carefully evaluated. The release of additive residues, bioactive compounds, or modified waste profiles into aquatic ecosystems can disrupt ecological balance and affect non-target organisms **(Burridge *et al.,* 2010; Rico *et al.,* 2012).** Furthermore, concerns regarding bioaccumulation, trophic transfer, and long-term ecological consequences are increasingly being raised **(Lulijwa *et al.,* 2020).** Future developments should prioritize the design and application of biodegradable, environmentally sustainable additives and promote comprehensive life-cycle assessments to ensure minimal environmental footprints and responsible aquaculture practices **(Henriksson *et al.,* 2012).**

6.4. Integration with Sustainable Aquaculture Practices

The use of feed additives must align with the broader objectives of sustainable aquaculture, including environmental stewardship, animal welfare, and economic viability **(FAO, 2020; Little *et al.,* 2016).** Additives should not only enhance fish health and productivity but also contribute to reducing the reliance on antibiotics, improving feed efficiency, and minimizing waste output **(Reverter *et al.,* 2014).** Integrated strategies that combine the use of functional feed additives with improved farming practices, efficient water management, and robust biosecurity measures are essential to build a more resilient, productive, and sustainable aquaculture sector **(Naylor *et al.,* 2021).**

6.5. Long-Term Effects and Safety

While the short-term benefits of feed additives are well-documented, their long-term effects on fish health, reproductive success, and overall sustainability in aquaculture systems remain less understood **(Hoseinifar *et al.,* 2017; Dawood *et al.,* 2020).** Chronic exposure to certain additives, particularly synthetic compounds, may result in unintended impacts on growth performance, immune system function, and metabolic health **(Zhou *et al.,* 2018).** Therefore, long-term studies are essential to evaluate cumulative effects, additive safety, and the potential for residual accumulation in fish products destined for human consumption **(Van Doan *et al.,* 2021).** Establishing comprehensive long-term safety profiles will not only enhance consumer confidence but also facilitate regulatory approval and compliance with food safety standards.

6.6. Precision Nutrition and Feed Formulation

As the field of aquaculture nutrition advances, the concept of precision nutrition is gaining increasing importance. This approach aims to customize fish diets based on species-specific nutrient requirements, health status, genetic background, and environmental conditions **(Glencross *et al.,* 2020; NRC, 2011).** Feed additives that can specifically modulate metabolic pathways or enhance stress responses are being considered for integration into precision formulations to improve growth efficiency, immune competence, and disease resistance on a case-by-case basis **(Le Boucher *et al.,* 2022).** Incorporating precision nutrition strategies can optimize feed utilization, reduce nutrient waste, and enhance the sustainability and resilience of aquaculture systems **(Hua *et al.,* 2019).**

6.7. Impact on Fish Behavior and Welfare

The effects of feed additives on fish behavior and welfare are often overlooked but are gaining increasing recognition. Certain additives can influence feeding behavior, social interactions, and stress responses, all of which directly impact fish welfare and farm productivity **(Huntingford *et al.,* 2006; Ashley, 2007).** Additives that promote well-being, reduce stress, or enhance resilience to handling could improve survival rates, health outcomes, and the overall quality of farmed fish (**Martins *et al.,* 2012).** Evaluating behavioral parameters, alongside traditional growth and health metrics, should become a standard part of additive efficacy assessments to ensure holistic benefits in aquaculture systems (**Arechavala-Lopez *et al.,* 2019).**

6.8. Cost-Benefit Analysis and Economic Considerations

A thorough cost-benefit analysis is crucial when evaluating the practical application of feed additives in commercial aquaculture.

While feed additives may improve growth rates, disease resistance, and feed conversion, their costs must be weighed against potential gains in fish production and farm profitability. Cost-effective alternatives or the development of more affordable sourcing methods, such as microbial or plant-derived additives, could increase the adoption of feed additives without significantly raising production costs. Economic assessments should be integrated into additive development and selection processes.

Table (3). Key Challenges and Research Directions for Feed Additives

Challenge	Description	Suggested Solutions	References
High production cost	Additives such as enzymes and nanoparticles (NPs) are often expensive to produce	Microbial or plant-based sourcing, optimization of lower inclusion rates	**Khosravi-Katuli *et al.* (2017)**
Inconsistent efficacy	Variable biological outcomes across different fish species and farming conditions	Species-specific trials, development of synergistic additive combinations	**Reverter *et al.* (2014); Ringø *et al.* (2018)**
Regulatory gaps	Lack of clear approval frameworks for many additives in global markets	Establishment of unified regulations and mandatory safety evaluations	**Bai *et al.* (2022)**
Stability in feed processing	Degradation of certain additives during pelleting or extrusion due to heat and pressure	Advanced encapsulation and coating technologies	**Adeoye *et al.* (2016)**
Consumer perception	Concerns regarding the use of "unnatural" ingredients, especially nanomaterials	Transparent labeling practices, preference for natural or plant-derived sources	**Hasan *et al.* (2024); Awad *et al.* (2017)**

Data presented in this table are compiled from peer-reviewed scientific literature, including **Khosravi-Katuli *et al.* (2017), Reverter *et al.* (2014), Ringø *et al.* (2018), Bai *et al.* (2022), Adeoye *et al.* (2016), Hasan *et al.* (2024), and Awad *et al.* (2017).**

7. Conclusion

The strategic use of feed additives in aquaculture has become increasingly vital for enhancing fish growth performance, health status, stress resilience, and environmental sustainability. A wide range of additives, including probiotics, prebiotics, phytogenics, organic acids, enzymes, immunostimulants, and antioxidants, have demonstrated significant functional benefits by improving nutrient utilization, modulating immune responses, mitigating oxidative stress, and enhancing disease resistance. Furthermore, the shift toward natural, eco-friendly, and synergistic additive formulations aligns well with the global movement toward sustainable aquaculture practices and consumer demand for safer, more responsible seafood products.

However, the successful application of feed additives faces notable challenges, including high production costs, variability in species-specific responses, limited dose standardization, stability issues during feed processing, and emerging concerns about long-term safety and environmental impacts. Addressing these gaps requires integrative research efforts focused on precision nutrition, additive synergism, behavioral and welfare impacts, and cost-effective innovations. Moreover, aligning additive development with market expectations for natural and clean-label products will be crucial for industry-wide acceptance.

Feed additives represent a powerful tool to optimize aquaculture production while promoting fish welfare, environmental health, and economic viability. Continued advancements in additive science, combined with sustainable management practices, will play a critical role in meeting the growing global demand for high-quality aquaculture products in the coming decades.

References

Abdel-Tawwab, M.; Khalil, R.H. and Ahmad, M.H. (2020b). Dietary supplementation to mitigate stress in aquaculture: A review. Aquaculture International*, 28*(2), 405–431. https://doi.org/10.1007/s10499-019-00478-1

Abdel-Tawwab, M.; Mousa, M.A.A. and Abbass, F.E. (2020a). Antioxident and growth-promoting effects of dietary vitamins C and E supplementation in fish. Aquaculture Nutrition, 26(3), 764–773. https://doi. org/ 10. 1111/anu.13035

Abou-Elgheit, E.; El-Bahr, S.M. and Abdel-Wanis, N.A. (2022). Effect of organic acid supplementation on growth performance, nutrient digestibility, and intestinal health of fish: A review. Aquaculture Research, 53(5), 1723–1734. https://doi.org/10.1111/are. 15785

Abu-Zahra, N.I.S.; Atia, A.A.; Elseify, M.M. and Soliman, S. (2023). Biological and histological changes and DNA damage in *Oreochromis niloticus* exposed to oxytetracycline: A potential amelioratory role of ascorbic acid. Aquaculture International, *32*(4), 3889–3916. https://doi.org/10.1007/s10499-023-01356-5

Abu-Zahra, N.I.S.; Atia, A.A.; Elseify, M.M.; Abass, M.E. and Soliman, S. (2025). Dietary Pelargonium Sidoides extract mitigates thermal stress in *Oreochromis niloticus*: Physiological and immunological insights. Veterinary Research Communications, *49*(3). https://doi.org/10.1007/s11259-025-10705-z

Abu-Zahra, N.I.S.; ElShenawy, A.M.; Ali, G.I.E.; Al-sokary, E.T.; Mousa, M.A. and El-Hady, H.A.M.A. (2024). *Mentha piperita* powder enhances the biological response, growth performance, disease resistance, and survival of *Oreochromis niloticus* infected with Vibrio alginolyticus. Aquaculture International, *32*(5), 6353–6379. https://doi. org/10. 1007/s10499-024-01469-5

Adeoye, A.A.; Jaramillo-Torres, A.; Fox, S.W.; Merrifield, D.L. and Davies, S.J. (2016). Supplementation of dietary phytase improves growth performance and digestibility of nutrients in tilapia fed plant-based diets. Aquaculture, 437, 15–24.

Ahmed, A.I.; El Asely, A.M. and El-Hais, A.M. (2022). Impact of functional feed additives on growth, health, and sustainability in aquaculture: A review. Aquaculture International, 30(3), 987–1005. https://doi. org/10. 1007/s10499-021-00759-5

Akrami, R.; Gharaei, A. and Mansour, M.R. (2022). Prebiotics as feed additives in aquaculture: Effects on growth, immune response, and disease resistance. Reviews in Aquaculture, 14(2), 778–800. https://doi.org/10.1111/ raq.12652

Arechavala-Lopez, P.; Cabrera-Álvarez, M.J.; Maia, C.M.; Saraiva, J.L. and Duncan, N.J. (2019). Welfare indicators for captive fish: A review. Fisheries Research, 211, 74–89. https://doi.org/10.1016/j. fishres. 2018. 10.033

Ashley, P.J. (2007). Fish welfare: Current issues in aquaculture. Applied Animal Behaviour Science, 104(3–4), 199–235. https:// doi.org/10.1016/j.applanim.2006.09.001

Awad, E. and Awaad, A. (2017). Role of medicinal plants on growth performance and immune status in fish. *Fish & Shellfish Immunology*, *67*, 40–54. https:// doi.org/10.1016/j.fsi.2017.05.034

Bai, S.C.; Hamidoghli, A. and Bae, J. (2022). Feed additives: An overview. In *Feed and Feeding Practices in Aquaculture* (pp. 195–229). Elsevier. https://doi.org/10.1016/ b978-0-12-821598-2.00015-1

Bagni, M.; Romano, N.; Finoia, M.G.; Abelli, L.; Scapigliati, G.; Tiscar, P.G. and Carnevali, O. (2005). Short- and long-term effects of a dietary yeast β-glucan (Macrogard) and alginate on immune response in sea bass (*Dicentrarchus labrax*). Fish & Shellfish Immunology*, 18*(4), 311–325.

Bricknell, I.R. and Dalmo, R.A. (2005). The use of immunostimulants in fish larval aquaculture. Fish & Shellfish Immunology, 19(5), 457–472.

Burridge, L.; Weis, J.S.; Cabello, F.; Pizarro, J. and Bostick, K. (2010). Chemical use in salmon aquaculture: A review of current practices and possible environmental effects. Aquaculture, 306(1-4), 7–23. https://doi. org/10. 1016/j.aquaculture.2010.05.020

Citarasu, T. (2010). Herbal biomedicines: A new opportunity for aquaculture industry. Aquaculture International*, 18*, 403–414.

Dawood, M.A.O. and Koshio, S. (2016). Recent advances in the role of probiotics and prebiotics in carp aquaculture: A review. Aquaculture, *454*, 243–251.

Dawood, M.A.O. and Koshio, S. (2019). Recent advances in the role of probiotics and prebiotics in carp aquaculture. Aquaculture*, 454*, 243–251.

Dawood, M.A.O.; Koshio, S. and Abdel-Daim, M.M. (2020). Impact of the application of dietary additives on the immune system and disease resistance of cultured finfish. Fish & Shellfish Immunology, 97, 268–282. https://doi.org/10.1016/j.fsi.2019.12.072

Dawood, M.A.O.; Koshio, S. and Esteban, M.Á. (2019). Beneficial roles of feed additives as immunostimulants in aquaculture: A review. Reviews in Aquaculture, 11(4), 1120 –1153. https://doi.org/10.1111/raq.12276

Dawood, M.A.O.; Koshio, S.; Esteban, M.Á. and Dadar, M. (2021). Beneficial roles of feed additives as immunostimulants in aquaculture: A review. Reviews in Aquaculture*, 13*(3), 1049–1101.

FAO (2022). The State of World Fisheries and Aquaculture 2022: Towards Blue Transformation*.* Food and Agriculture Organization of the United Nations, Rome. https://doi.org/10.4060/cc0461en

FAO (Food and Agriculture Organization of the United Nations). (2020). The State of World Fisheries and Aquaculture 2020: Sustainability in Action. Rome: FAO. https://doi.org/10.4060/ca9229en

Gatlin, D.M.; Barrows, F.T.; Brown, P.; Dabrowski, K.; Gaylord, T.G.; Hardy, R.W. and Wurtele, E. (2007). Expanding the utilization of sustainable plant products in aquafeeds: A review. Aquaculture Research, 38(6), 551–579. https://doi.org/10.1111/j.1365-2109.2007.01704.x

Giri, S.S.; Sen, S.S.; Saha, S.; Sukumaran, V. and Park, S.C. (2019). Improvement of antioxidant status and disease resistance in aquaculture: Role of medicinal plants. Reviews in Aquaculture, *11*(4), 1175–1191.

Glencross, B.D.; Booth, M. and Allan, G.L. (2020). A feed is only as good as its ingredients – A review of ingredient evaluation strategies for aquaculture feeds. Aquaculture Nutrition, 26(6), 1868–1881. https://doi.org/10.1111/anu.13138

Gouveia, L.; Batista, A.P.; Miranda, A.; Empis, J. and Raymundo, A. (2003). Chlorella vulgaris and Spirulina maxima biomass as colorant in food emulsions. European Food Research and Technology, 216(6), 412 –416.

Hai, N.V. (2015). The use of probiotics in aquaculture. Journal of Applied Microbiology, 119(4), 917–935.

Harikrishnan, R.; Balasundaram, C. and Heo, M.S. (2011). Impact of plant products on innate and adaptive immune system of cultured finfish and shellfish. Aquaculture, *317*(1-4), 1–15.

Hasan, M.M.; Rahman, M.M.; Islam, M.S. and Karim, M.M. (2024). Application of nanoparticles in aquafeeds: Impacts on fish growth, antioxidant responses, and disease resistance. Aquaculture Nutrition, 30(1), 1–12. https://doi.org/10.1111/anu.13985

Henriksson, P.J.G.; Rico, A.; Troell, M.; Klinger, D.H.; Buschmann, A.H.; Saksida, S. and Zhang, W. (2012). Unpacking factors influencing antimicrobial use in global aquaculture and their implications for management: A review. Science of The Total Environment, 457-458, 490–500. https://doi.org/10.1016/j.scitotenv.2013.04.038

Hernández, M.D.; Martínez, F.J.; Jover, M. and García, B.G. (2008). Effect of partial replacement of fish meal by soybean meal in sharpsnout seabream (*Diplodus puntazzo*) diets. Aquaculture, 277(3–4), 292–300.

Hoseinifar, S.H.; Sun, Y.Z.; Wang, A. and Zhou, Z. (2017). Probiotics as means of diseases control in aquaculture: A review of current knowledge and future perspectives. Frontiers in Microbiology, 8, 2429. https://doi.org/10.3389/fmicb.2017.02429

Hua, K.; Cobcroft, J.M.; Cole, A.; Condon, K.; Jerry, D.R.; Mangott, A. and Zeng, C. (2019). The future of aquatic protein: Implications for protein sources in aquaculture diets. One Earth, 1(3), 316–329. https://doi.org/10.1016/j.oneear.2019.10.018

Huntingford, F.A.; Adams, C.; Braithwaite, V.A.; Kadri, S.; Pottinger, T.G.; Sandoe, P. and Turnbull, J.F. (2006). Current issues in fish welfare. Journal of Fish Biology, 68 (2), 332–372. https://doi.org/10.1111/j.0022-1112.2006.001046.x

Khosravi-Katuli, K.; Prato, E.; Lofrano, G.; Guida, M.; Vale, G. and Libralato, G. (2017). Effects of nanoparticles in species of aquaculture interest. *Environmental Science and Pollution Research*, *24*(21), 17326–17346. https://doi.org/10.1007/s11356-017-9360-3

Kiron, V. (2012). Fish immune system and its nutritional modulation for preventive health care. Animal Feed Science and Technology, 173(1–2), 111–133. https://doi.org/10.1016/j.anifeedsci.2011.12.015

Le Boucher, R.; Vandeputte, M.; Dupont-Nivet, M. and Quillet, E. (2022). Precision fish farming: Advances in genomics, nutrition and health management to improve aquaculture sustainability. Reviews in Aquaculture, 14(1), 166–186. https://doi.org/10.1111/raq.12634

Little, D.C.; Newton, R.W. and Beveridge, M.C.M. (2016). Aquaculture: A rapidly growing and significant source of sustainable food? Status, transitions and future outlook. In Food Security (Vol. 8, pp. 571–583). https://doi.org/10.1007/s12571-016-0561-9

Lulijwa, R.; Rupia, E.J. and Alfaro, A.C. (2020). Antibiotic use in aquaculture, policies and regulation, health and environmental risks: A review of the top 15 major producers. Reviews in Aquaculture, 12(2), 640–663. https://doi.org/10.1111/raq.12344

Manafi, M. (2022). Mycotoxin binders in aquafeeds: Mechanisms and practical applications. Aquaculture Reports*, 24*, 101108.

Manning, B.B.; Abbas, H.K. and Wolters, W.R. (2005). Response of Nile tilapia to diets containing aflatoxin-contaminated grain and a hydrated sodium calcium aluminosilicate (HSCAS) additive. Aquaculture, 246(1–4), 239–255.

Maas, R.M.; Verdegem, M.C.J.; Stevens, T.L. and Schrama, J.W. (2020). Effect of exogenous enzymes (phytase and xylanase) supplementation on nutrient digestibility and growth performance of Nile tilapia (Oreochromis niloticus) fed different quality diets. *Aquaculture*, *529*, 735723. https://doi.org/10.1016/j.aquaculture.2020.735723

Martins, C.I.M.; Galhardo, L.; Noble, C.; Damsgård, B.; Spedicato, M.T.; Zupa, W. and Kristiansen, T.S. (2012). Behavioural indicators of welfare in farmed fish. Fish Physiology and Biochemistry, 38(1), 17–41. https://doi.org/10.1007/s10695-011-9518-8

Merrifield, D.L.; Dimitroglou, A.; Foey, A.; Davies, S.J.; Baker, R.T.M.; Bøgwald, J.; Castex, M. and Ringø, E. (2010). The current status and future focus of probiotic and prebiotic applications for salmonids. Aquaculture, 302(1–2), 1–18. https://doi.org/10.1016/j.aquaculture.2010.02.007

Naylor, R.L.; Hardy, R.W.; Buschmann, A.H.; Bush, S.R.; Cao, L.; Klinger, D.H. and Troell, M. (2021). A 20-year retrospective review of global aquaculture. Nature, 591(7851), 551–563. https://doi.org/10.1038/s41586-021-03308-6

Ng, W.K. and Koh, C.B. (2017). The utilization and mode of action of organic acids in the diets of aquatic animals. Reviews in Aquaculture, 9(4), 342–368.

NRC (National Research Council). (2011). Nutrient Requirements of Fish and Shrimp. Washington, DC: The National Academies Press. https://doi.org/10.17226/13039.

Reverter, M.; Bontemps, N.; Lecchini, D.; Banaigs, B. and Sasal, P. (2014). Use of plant extracts in fish aquaculture as an alternative to chemotherapy: Current status and future perspectives. Aquaculture, 433, 50–61. https://doi.org/10.1016/j. Aquaculture. 2014. 05.048

Rico, A.; Phu, T.M.; Satapornvanit, K.; Min, J.; Shahabuddin, A.M.; Henriksson, P.J.G. and Van den Brink, P.J. (2012). Use of veterinary medicines, feed additives and probiotics in four major internationally traded aquaculture species farmed in Asia. Aquaculture, 412-413, 231–243. https://doi. org/10. 1016/j.Aquaculture.2013.07.015

Ringø, E.; Hoseinifar, S.H.; Ghosh, K.; Doan, H.V.; Beck, B.R. and Song, S.K. (2018). Lactic acid bacteria in finfish—an update. Frontiers in Microbiology, 9, 1818. https://doi.org/10.3389/fmicb.2018.01818

Ringø, E.; Olsen, R.E.; Gifstad, T.Ø.; Dalmo, R.A.; Amlund, H.; Hemre, G.I. and Bakke, A.M. (2010). Prebiotics in aquaculture: A review. Aquaculture Nutrition*, 16* (2), 117–136.

Santacroce, M.P.; Conversano, M.C.; Casalino, E.; Lai, O.; Zizzadoro, C.; Centoducati, G. and Crescenzo, G. (2021). Phytochemicals and essential oils in aquaculture: Their roles in fish health and pathogen control. Frontiers in Veterinary Science*, 8*, 614131. https://doi.org/10.3389/fvets. 2021. 614131

Sidiq, M.J.; Jayaraj, E.G.; Rathore, S.S.; Bhat, R.A.H.; Mamun, M.A.A. and Khandagale, A.S. (2023). Ameliorative role of dietary acidifier potassium formate on growth metrics, blood chemistry, gut health and well-being indices of rohu, Labeo rohita fingerlings. *Fish Physiology and Biochemistry*, *49*(1), 19–37. https://doi.org/10.1007/ s10695-023-01171-y

Silva, T.S.; Rosas, C. and Cuzon, G. (2015). Stress and stress management in aquaculture. In Aquaculture Engineering and Technology (pp. 313-336). CRC Press.

Van Doan, H.; Hoseinifar, S.H.; Sringarm, K. and Dawood, M.A.O. (2020). Effects of dietary supplementation of probiotics, prebiotics, and synbiotics on growth performance and disease resistance of aquaculture species: A review. *Aquaculture Research*, 51(2), 509–528. https://doi.org/10.1111/are.14471

Van Doan, H.; Hoseinifar, S.H.; Sringarm, K.; Jaturasitha, S.; Dawood, M.A.O. and Esteban, M.Á. (2021). Effects of using medicinal herbs in aquaculture feeding on growth, immune response and disease resistance of fish and shrimp: A review. Aquaculture, 543, 736898. https://doi.org/10.1016/ j.aquaculture.2021.736898

Wang, C.; Huang, J.; Liu, X. and Xu, H. (2023). Probiotics as dietary supplements for sustainable aquaculture: Advances and prospects. Aquaculture Research, 54(2), 687–698. https://doi.org/10.1111/are.16189

Yousefi, M.; Hoseinifar, S.H. and Van Doan, H. (2023). Dietary immunostimulants and fish health: Current knowledge and future perspectives. Fish & Shellfish Immunology, 132, 108504. https://doi.org/10.1016/j. fsi. 2023.108504

Zheng, Z.L.; Tan, J.Y.W.; Liu, H.Y.; Zhou, X.H.; Xiang, X. and Wang, K.Y. (2021). Effects of dietary β-glucan on growth performance and immune responses of fish: A meta -analysis. Aquaculture Reports*, 19*, 100564.

Zhou, Z.; Ringø, E.; Olsen, R.E. and Song, S.K. (2018). Dietary effects of soybean products on gut microbiota and immunity of aquatic animals: A review. Aquaculture Nutrition, 24(3), 644–665. https:// doi.org/10.1111/anu.12619