fishes

IMPACT FACTOR 2.4

CITESCORE 3.0

Review

Feed Additives in Aquaculture: Benefits, Risks, and the Need for Robust Regulatory Frameworks

Ekemini Okon, Matthew Iyobhebhe, Paul Olatunji, Mary Adeleke, Nelson Matekwe and Reuben Okocha

Special Issue
Advances in Aquaculture Feed Additives

Edited by
Prof. Dr. Adolfo Jatobá and Prof. Dr. Delano Dias Schleder

MDPI

https://doi.org/10.3390/fishes10090471

fishes

MDPI

Review

Feed Additives in Aquaculture: Benefits, Risks, and the Need for Robust Regulatory Frameworks

Ekemini Okon [1,2,*], Matthew Iyobhebhe [3], Paul Olatunji [4], Mary Adeleke [2], Nelson Matekwe [5] and Reuben Okocha [2,*]

1 Faculty of Bioscience Engineering, Ghent University, 9000 Ghent, Belgium
2 Department of Agriculture, Landmark University, Omu-Aran 251103, Kwara State, Nigeria; themaryadeleke@gmail.com
3 Department of Biochemistry, Landmark University, Omu-Aran 251103, Kwara State, Nigeria; iyobhebhematthew@gmail.com
4 Freshwater and Oceanic Sciences Unit of Research, University of Liege, Sart Tilman, 4000 Liège, Belgium; olatunji.o.paul@gmail.com
5 Department of Agriculture, Environmental Affairs, Rural Development and Land Reform, Veterinary Services, Kimberley 8300, South Africa; nmatekwe@daerl.co.za
* Correspondence: okon.ekemini@lmu.edu.ng or okon.ekeminimoses@gmail.com (E.O.); okocha.reuben@lmu.edu.ng (R.O.)

Abstract

Aquaculture currently supplies over half of the world's fish and relies heavily on feed additives to enhance growth, improve feed efficiency, and increase disease resistance. This review consolidates peer-reviewed studies identified through targeted searches of Web of Science, Scopus, and Google Scholar, focusing on aquaculture feed additives. It emphasizes the principal classes of additives employed in finfish and shrimp cultivation, such as natural immunostimulants (including beta-glucans and nucleotides), probiotics, prebiotics, synbiotics, phytogenics, enzymes, and synthetic nutrients. For each, it summarizes their mechanisms of action, commonly reported inclusion rates, production outcomes, environmental risks, and regulatory statuses. Evidence indicates that immunostimulants enhance innate defences (including phagocyte activity and cytokine responses). Probiotics and prebiotics, on the other hand, regulate gut microbiota and barrier function. Phytogenics offer antimicrobial and antioxidant effects, and synthetic additives provide targeted nutrients or functional compounds that support growth and product quality. Where data are available, typical application ranges include probiotics in the order of 10^4–10^9 CFU per gram, prebiotics at approximately 2–10 g per kilogram, and pigments or antioxidants (such as astaxanthin) at 50–100 mg per kilogram. Significant gaps exist, notably the absence of species-specific dose–response data for tropical and subtropical aquaculture species, as well as limited experimental evidence regarding additive–additive interactions under commercial rearing conditions. Additional gaps include long-term ecological fate, regional regulatory discrepancies, and species-specific dose–response relationships. It is recommended that mechanistic studies employing omics approaches, standardised dose–response trials, and harmonized risk assessments be conducted to promote the sustainable and evidence-based application of feed additives.

Keywords: aquaculture; feed additives; fish nutrition; shrimp nutrition; fish health; immune response

Key Contribution: This paper offers a comprehensive overview of traditional and emerging feed additives in aquaculture, incorporating mechanistic insights, typical application

check for updates

Academic Editors: Qiyou Xu, Adolfo Jatobá and Delano Dias Schleder

Received: 18 July 2025
Revised: 16 September 2025
Accepted: 16 September 2025
Published: 22 September 2025

Citation: Okon, E.; Iyobhebhe, M.; Olatunji, P.; Adeleke, M.; Matekwe, N.; Okocha, R. Feed Additives in Aquaculture: Benefits, Risks, and the Need for Robust Regulatory Frameworks. *Fishes* **2025**, *10*, 471. https://doi.org/10.3390/fishes10090471

ranges, and measurable indicators of performance and health. It provides a critical assessment of factors influencing the practical adoption of these technologies, including efficacy, cost-effectiveness, availability, regulatory constraints, and environmental considerations. Notable contributions include a comparative table that details conventional additives alongside next-generation approaches (e.g., bacteriophage–probiotic cocktails, postbiotics, and nano-encapsulated bioactives). We also provide a summary of key research gaps and strategic recommendations for sustainable application across various species and production systems.

1. Introduction

Fish and shrimp aquaculture continue to grow rapidly due to increasing global demand [1,2]. According to the FAO SOFIA 2024 report, global fisheries and aquaculture production in 2022 reached a record 223.2 million tonnes, including 130.9 million tonnes from aquaculture. This marks the first time aquaculture has surpassed capture fisheries in aquatic animal production (94.4 million tonnes vs. 91.0 million tonnes) [3].

Furthermore, unlike most land-based agricultural food production systems, over 95% of global aquaculture output occurs in developing countries, with a yearly growth rate of 6.13% [3]. However, the intensification of aquaculture has raised various environmental concerns regarding its potential effects on aquatic life, amid efforts to achieve sustainability [4].

In response to the growing demand for fish and shrimp, there is an increasing interest in using diverse feed additives to enhance the health and performance of these species [5]. Additionally, fish and shrimp production has experienced significant growth due to technological advancements, improved breeding methods, and the availability of high-quality feed [6]. Specifically, various feed sources, including plant and animal products, minerals, and other additives, are utilised to meet the growing demands of this industry. These feed additives have been shown to reduce reliance on natural aquatic products, resulting in higher yields per unit of water surface area or volume at grow-out facilities [7]. This is due to their various component ingredients, which are formulated to meet the nutritional requirements of aquatic animals, support their immune system function, and promote growth [5].

Globally, aquaculture feeds account for approximately 3.6% of the total compound feed volume used in animal production [7]. Despite their relatively modest proportion, the importance of aquaculture feeds should not be overlooked [8]. Feed additives in aquaculture play a crucial role in maintaining health, reducing costs, promoting robust growth, and enhancing yield potential across various aquatic species. These feeds are formulated to provide balanced nutrition, thereby meeting the dietary needs of aquatic animals [5,9].

For this review, feed additives are defined as intentionally added, non-nutritive or functional substances. They are included in formulated aquafeeds or delivered as supplements to modulate growth, feed utilisation, health, product quality, or feed stability. Different feed additives are employed to optimise the intake, digestion, absorption, and transportation of dietary nutrients in aquatic feeds. These feed additives encompass a wide range of substances, including probiotics, prebiotics, immunostimulants, enzymes, and essential nutrients [9]. They are typically incorporated into aquafeed formulations to supplement the nutritional requirements of farmed fish and shrimp [9]. Feed additives can further enhance growth rates and feed conversion efficiency by supporting digestive health and nutrient utilisation, ultimately leading to improved production outcomes for farmers [8].

Furthermore, certain additives have demonstrated immune-stimulatory properties, enhancing the disease resistance of farmed species and reducing the need for antibiotics [10]. These additives are crucial for optimising the digestion and absorption of nutrients, leading to enhanced overall health and performance [9]. Feed additives, such as probiotics, prebiotics, enzymes, and organic acids, work together to support a balanced microbial community within the digestive systems of animals [9,11]. Probiotics introduce beneficial bacteria that assist in digestion and improve nutrient absorption. Moreover, prebiotics nourish these helpful microorganisms by boosting their growth and activity levels [12].

On the other hand, enzymes are essential for breaking down complex feed components, such as fibres and non-starch polysaccharides, into simpler forms that fish and shrimp can more easily absorb [13]. Additionally, organic acids like formic, propionic, and butyric acids help establish an optimal pH environment in the digestive systems of these aquatic animals [14]. This balanced environment not only suppresses the growth of harmful bacteria but also encourages the growth of beneficial bacteria [14].

However, the utilisation of feed additives in aquaculture, encompassing fish and shrimp farming, poses some challenges. Recent research has focused on understanding the impact of feed additives on the aquatic environment [15]. This emphasizes the importance of carefully selecting suitable additives and ensuring the correct dosage to prevent adverse environmental impacts [15,16]. Earlier studies documented that certain additives can have a negative impact on the environment when released into aquatic ecosystems. Therefore, responsible use and sustainable practices are essential, involving the careful consideration of various key factors [8,15,16].

Environmental concerns linked to the use of additives now include documented outbreaks of antibiotic-resistant infections in aquaculture systems. In Southeast Asia, the presence of multi-drug-resistant *E. coli* and other pathogens has been linked to feed containing antibiotics and poor waste management. This is particularly notable in shrimp farms in Thailand and integrated fish–chicken systems in Vietnam [17,18]. These findings highlight the need to adopt sustainable practices, implement rigorous monitoring, and enforce regulatory measures. Taking these steps is essential for tackling these challenges and ensuring the sustainability of aquaculture in the long term.

Although several additive classes have demonstrated benefits for growth and immunity, inconsistencies in comparisons across species and formulations hinder the standardization of dosages. Furthermore, the environmental fate and long-term ecological effects of many additives are not well understood, and regulatory approaches are inconsistent across regions. This limits the safe and uniform use of these additives. Therefore, this review provides a comprehensive overview of the impact of feed additives on the health and growth of fish and shrimp. It focuses on natural immunostimulants, probiotics, prebiotics, synthetic feeds, and phytogenics. The specific objectives are (1) to synthesize experimental and regulatory evidence on the main classes of aquafeed additives and their typical application ranges; (2) to summarize known mechanisms of action and measurable endpoints used to assess additive efficacy and safety; and (3) to identify key knowledge gaps and propose research and regulatory priorities for sustainable use. This study aims to assist fish and shrimp farmers, researchers, policymakers, and stakeholders in the aquaculture industry in making evidence-based decisions for sustainable aquafeed use.

To ensure a comprehensive and balanced synthesis, relevant literature was identified through searches of Scopus, Web of Science, and Google Scholar using combinations of keywords such as "aquaculture," "feed additives," "immunostimulants," "prebiotics," "probiotics," "synbiotics," "phytogenics," and "postbiotics." Studies were included if they were published in English and addressed fish or shrimp species of aquacultural relevance. Priority was given to research that reported measurable outcomes related to growth performance, feed utilisation, immune modulation, physiological responses, or environmental impact.

2. Natural Immunostimulants as Feed Additives in Fish and Shrimp Diets

Natural immunostimulants are compounds that enhance or stimulate the immune system upon exposure to foreign agents [19]. These substances are derived from diverse sources, including plants such as herbs, seaweed, fruits, and vegetables, as well as other naturally occurring compounds [20]. Among the natural immunostimulants, polysaccharides (beta-glucans) and nucleotides have undergone extensive research concerning their application in fish and shrimp to sustain or improve their health [21].

Several polysaccharides, including beta-glucans, mannan oligosaccharides (MOS), chitosan, and alginates, have demonstrated immunomodulatory properties in fish and shrimp [22–26]. Beta-glucans are complex polysaccharides found abundantly in the cell walls of bacteria, fungi, and the extracellular matrix of yeast [21]. They induce immune cells, such as neutrophils and macrophages, thereby activating and stimulating the immune response [27]. Beta-glucan binds to pattern-recognition receptors, including Dectin-1 (CLEC7A), complement receptor 3 (CR3), and Toll-like receptors (TLRs), on immune cells. This receptor engagement triggers intracellular signalling cascades, particularly via Syk kinase, PKCδ, and the CARD9–BCL10–MALT1 (CBM) complex, leading to NF-κB activation, the production of inflammatory cytokines, a respiratory burst, and enhanced phagocytosis [28,29].

Recent research on beta-glucan has revealed promising findings regarding its immunomodulatory effects in fish and shrimp [30]. In channel catfish (*Ictalurus punctatus*), exposure to beta-glucan significantly increased the phagocytic rates of neutrophils and macrophages, accompanied by the upregulation of genes related to phagocytosis and receptor signalling pathways [31]. The most important aspect of beta-glucan is its ability to substantially enhance the activity of phagocytes. This includes granulocytes and monocytes, which then differentiate into macrophages and dendritic cells. These phagocytes play a crucial role in preventing infections by ingesting potentially dangerous pathogens [32]. Stimulating phagocytes via beta-glucans triggers a series of events that improve immune defence mechanisms. This increases the immunity and resilience of aquatic organisms against various pathogenic agents [33].

The profound impact of beta-glucans on modulating immunological responses within cells derived from the intestinal mucosa cannot be overemphasised. This is important considering their significance for maintaining optimal well-being among fish and shrimp species [30]. Moreover, beta-glucan modifies diet activity levels, which can enhance fish resistance to infections transmitted through the primary route (i.e., the gut) [34,35]. Furthermore, beta-glucans have demonstrated favourable immunomodulatory effects in fish and shrimp [35,36]. This suggests that beta-glucans may be a valuable supplement for enhancing resistance to infectious diseases and improving productivity in fish and shrimp farming.

Besides beta-glucans and polysaccharides, nucleotides are essential components of DNA and RNA, playing a crucial role in the biological processes of many animals. Nucleotides substantially enhance the immune response by stimulating the production of antibodies and other essential immune cells in juveniles of the Pacific white shrimp *Litopenaeus vannamei* [37]. The immunomodulatory effects of these compounds on aquatic animals have been recently investigated, yielding promising results for their efficacy when administered at optimal dosages and for suitable species and durations that support immune enhancement without adverse effects [38,39]. Furthermore, the administration of dietary supplements containing high levels of nucleotides augmented the immune response, thereby facilitating the production of essential antibodies, known as immunoglobulins, which are active during viral episodes [39].

Research has further demonstrated that the inclusion of nucleotide supplements can enhance activity levels responsible for pathogen eradication during infection, while concurrently promoting the growth of beneficial bacteria to support balanced microbiota processes [40]. Consequently, maintaining an optimal microbiota balance promotes robust intestinal health, minimises disease susceptibility, and fosters overall well-being [12]. In aquatic species, such immunostimulants may be administered through various methods, including incorporation into feed, immersion, or injection, to attain targeted immunological effects.

Fish and Shrimp Immune Response to Natural Immunostimulants as a Feed Additive

Despite anatomical differences between vertebrate and invertebrate immune systems, dietary polysaccharides stimulate comparable innate immune mechanisms in fish and shrimp. In both groups, supplementation enhances phagocytic activity, respiratory burst, lysozyme and complement activity, and pathogen resistance [22,41–46]. In fish populations, administering beta-glucans through immersion, food inclusion, or injection is effective in enhancing immunological responses [47,48]. A strong immune system in fish protects them against diseases; therefore, boosting their immune response with beta-glucans can enhance overall health and reduce susceptibility to diseases [24,30]. Nevertheless, further research is required to ascertain the optimal dosages and methods of administration. Thus, it is necessary to investigate the long-term effects and interactions with other essential dietary components to evaluate the practical application of beta-glucans as immunostimulants specifically within the contexts of ichthyological and crustacean aquaculture. Additionally, the inclusion of specific polysaccharides in fish and shrimp feed enhances growth performance by improving nutrient uptake and stimulating immune responses [25]. These polysaccharides provide an ecologically sustainable alternative to synthetic options, owing to their low toxicity levels and easy biodegradability, making them a safe choice for use in aquaculture [23].

In shrimp, the immune response to natural immunostimulants is a relatively new research area that has gained significant global attention in recent years [49]. Beta-glucans have also shown promising results for enhancing a shrimp's immune response; however, they exhibit limitations when treating certain infections [34,50]. Despite these limitations, a significant understanding of their complex immune system is crucial for developing robust strategies that enhance disease resistance in shrimp. In addition, plant extracts and compounds derived from algae have demonstrated potential as immunostimulant sources, with studies revealing an increase in antibody production [49,51,52]. For instance, supplementation with algae extract significantly increased antibody cell synthesis in shrimp [53]. These consistent patterns suggest that mechanistic insights from one taxon can often inform application in the other, although dose optimisation remains species-specific. However, efficacy may vary across species and life stages, and long-term effects are not yet fully understood, requiring further research.

3. Probiotics and Prebiotics as Feed Additives in Fish and Shrimp Diets

There is a rapidly growing body of literature indicating the success of probiotics and prebiotics in immunomodulation (innate, cellular, and humoral immune responses). Probiotics are considered to be living microorganisms administered orally for health benefits [54]. They can alter the microflora (by implantation or colonisation) in a specific host's compartment, exerting beneficial health effects on the host [55]. On the other hand, prebiotics are indigestible fibres that enhance the growth of beneficial commensal gut bacteria, resulting in improved host health [56]. These beneficial effects of prebiotics are due to by-products derived from the fermentation of intestinal commensal bacteria [57].

Among the many health benefits attributed to probiotics and prebiotics, the modulation of the immune system is one of the most anticipated benefits (Figure 1), and it can stimulate systemic and local immunity [58] by directly enhancing the innate immune response, including phagocytosis, neutrophil activation, alternative complement system activation, and lysozyme activity [59]. In some cases, they improve growth, such as increasing size and weight gain, and could act as alternative antimicrobial compounds in fish and shrimp [60].

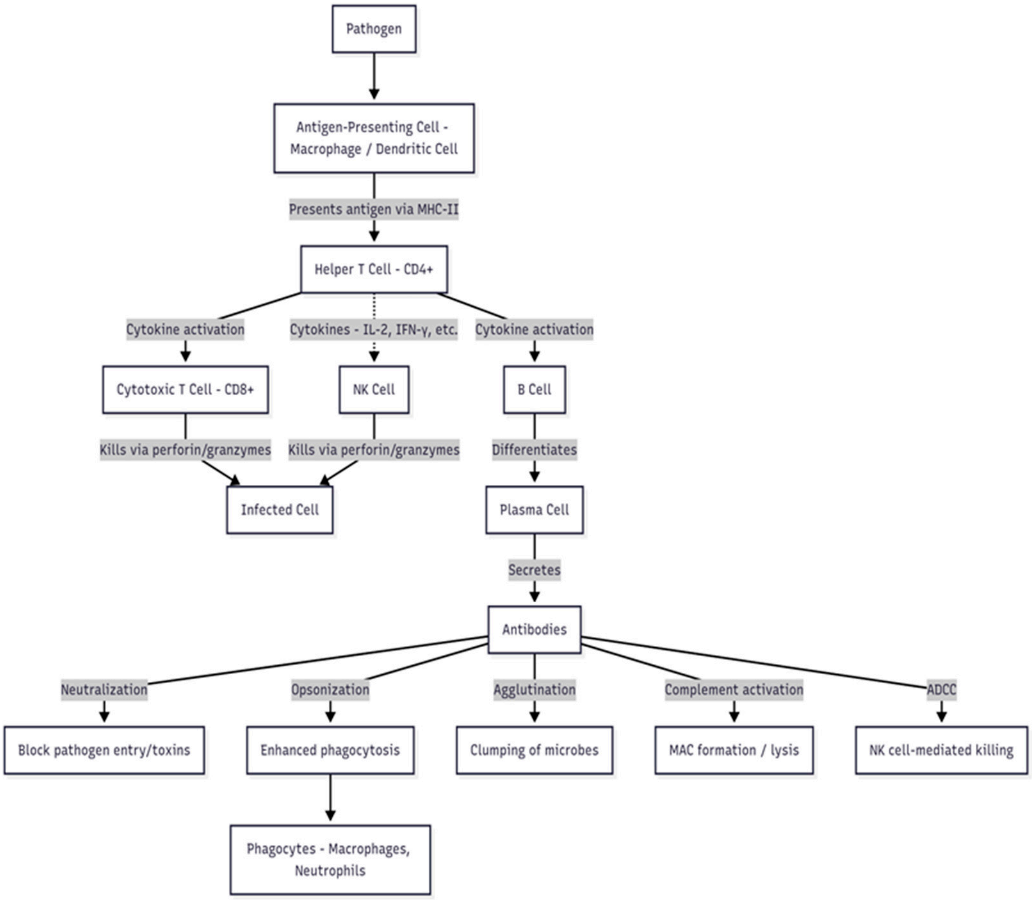

Figure 1. The cellular/humoral immunity interactions in fish and shrimp.

3.1. Immune Response of Fish to Probiotics and Prebiotics as Feed Additives

The integration of probiotics into the diets of fish and shrimp has been shown to have a positive impact on both cellular and humoral immunity, thereby significantly enhancing the immune system's functionality [61]. These beneficial microorganisms have the capacity to activate T and B lymphocytes, which are essential elements of the adaptive immune response [62]. The interaction between these two cell types results in an improved defence mechanism against pathogens and supports the development of long-lasting immunity [58,63]. Moreover, probiotics can augment antibody production by stimulating B cells that generate specific antibodies targeting pathogens within a humoral immune response, ultimately reducing the risk of infections in fish [64]. Furthermore, probiotics influence T-cell activity, a vital facet of the immune system. T lymphocytes are responsible for recognising and eliminating infected cells while mediating other immune responses, indicating that probiotics facilitate a more efficacious cellular immune response by modulating various T cell subsets in fish [65].

Probiotics can directly affect the immune cells and indirectly support their function by strengthening the gut barrier [66]. This is important in fish health, as the gut serves as a vital interface between the body's external environment and its immune system. Thus, having a robust intestinal barrier ensures pathogenic microorganisms cannot enter, grow, or survive in the fish's body systems [67]. Primarily, probiotics impact fish immune system through various mechanisms, including enhancing the integrity of the gut barrier by promoting mucus production, strengthening tight junctions between cells, and inhibiting the growth of harmful bacteria [58]. These actions ultimately lead to improved immune responses on both innate and adaptive levels. However, not all strains of probiotics produce identical effects when used as feed additives [68,69].

The dosage of probiotic supplements in fish may influence their efficacy in boosting immunological function [70] (Table 1). Each fish has a distinctive composition of gut microbiota, which may further influence individual responses to probiotic treatments for immune support [71]. Notably, probiotics impact humoral immunity, and certain strains of probiotics have been reported to positively influence immunoglobulin production, specifically secretory IgA [58,72]. These findings emphasize the significance of probiotics as feed additives for fish and shrimp, promoting improved health [73]. Despite promising findings regarding the potential benefits of probiotics for immune enhancement, further comprehensive studies are needed to elucidate their mechanisms and optimise their safe and effective use.

Table 1. Probiotic dosage and immunological effects in fish. Arrow facing upwards indicate an increase.

Probiotic Strain (Fish Species)	Dosage	Observed Immune Effects	Source
Bacillus subtilis E20 (*Epinephelus coioides*)	1×10^4–1×10^8 CFU g^{-1} feed	↑ Lysozyme, phagocytosis, superoxide dismutase (SOD), serum ACP	[74]
B. subtilis + fructooligosaccharides—FOS (*Trachinotus ovatus*)	1.05–5.62 $\times 10^7$ CFU g^{-1} feed + 0.2% or 0.4% FOS	↑ Specific growth rate (SGR), lysozyme, disease resistance, serum ACP	[7]
B. subtilis + *B. licheniformis* (*Oreochromis niloticus*)	0–10 g kg^{-1} feed	↑ Lysozyme, SGR protease, anti-protease, SOD, and immunoglobulin	[75]
Lactobacillus plantarum (Ep-M1) (*Litopenaeus vannamei*)	5×10^8 CFU g^{-1} feed	↑ SGR, SOD, immunometabolism, survival	[76]
Enterococcus casseliflavus (EC-001) (*Cyprinus carpio*)	1×10^7–1×10^9 CFU g^{-1} feed	↑ SGR, lysozyme, disease resistance, serum Acid Phosphatase (ACP)	[77]
Lactobacillus rhamnosus (*Oncorhynchus mykiss*)	1×10^6 CFU g^{-1} feed	↑ Weight gain, SOD, immunometabolism, lysozyme, disease resistance	[78]
Shewanella putrefaciens (Pdp11) (*Solea senegalensis*)	1×10^7 CFU g^{-1} feed	↑ Stress tolerance, disease resistance, and gut microbiota modulation	[79]

On the other hand, prebiotics serve as an energy source for the gut microbiota, thereby improving the immune system of aquatic animals and promoting general growth [24,80]. One good example of prebiotics that can stimulate an immune response is immunosaccharides [81]. Immunosaccharides can be considered an alternative to antibiotics in managing the health of aquatic animals in aquaculture [82,83].

Controlling fish diseases involves the use of vaccination rather than antibiotic treatments in aquaculture [84]. However, some diseases still lack available vaccines or are still under development. Therefore, alternative strategies have gained interest in recent years as supplements to vaccination and to reduce unnecessary antibiotic use. One strategy to supplement vaccination is the use of prebiotics, given their role in intestinal microbiota in fish and shrimp [85]. The microorganisms found within the caeca-colon ferment prebiotics, leading to the modification of the colonic microbiota and changes in the gut. This results from the utilisation of oligosaccharides by anaerobic bacteria, especially bifidobacteria, as a substrate, thereby eliminating the growth of harmful and putrefactive bacteria that can cause diseases [86].

Additional strategies to complement vaccination through the use of prebiotics encompass the stimulation of gut microbiota development or the activation of innate immune mechanisms [67]. The microbiota generate substances that activate the immune system and bolster the host's defences against infections [87]. For instance, the non-specific immune system of grass carp (*Ctenopharyngodon idella*), gilt-head seabream (*Sparus aurata*), and hybrid catfish (*Pangasianodon gigas* × *Pangasianodon hypophthalmus*) showed a positive response to the supplementation of mannan oligosaccharides in their diet [88–90]. Moreover, incorporating mannan oligosaccharides at a rate of 0.4% into the diet of gilt-head seabream improved their immune system. It increased their resistance to bacterial infections when directly introduced into the gut, a common site of infection in fish [91,92].

3.2. The Immune Response of Shrimps to Probiotics and Prebiotics as Feed Additives

The shrimp aquaculture sector is experiencing rapid growth, and the utilisation of prebiotics and probiotics is becoming increasingly popular [93]. Studies have shown the immune response of shrimps to probiotics, including the effects of short-chain fructooligosaccharides (FOS) supplementation on Pacific white prawn (*Litopenaeus vannamei*) [94]. Furthermore, Grobiotic®, a prebiotic dietary supplement for growth and health management in Pacific white shrimp (*Litopenaeus vannamei)*, showed improved survival rates when cultured in a low-salinity water level of 2 ppt [95]. However, the specific mechanisms responsible for this enhanced survival under low-salinity conditions have yet to be determined [96], as the optimal salinity for their growth and survival is between 20 and 25 ppt [97]. Furthermore, prebiotics have been demonstrated to alter the microbial community in the gastrointestinal tract, improving non-specific immune responses [12].

Research has shown that probiotics can improve shrimp's immunity against pathogenic bacteria and viruses [98]. For instance, it was observed that *Lactobacillus plantarum* could enhance the non-specific immune response in *Litopenaeus vannamei* when it is exposed to *Vibrio harveyi*. Further research has demonstrated that *Bacillus subtilis* WB60 enhanced the growth performance and immune response of shrimps [99]. *Pediococcus pentosaceus* has also been recognised as a potential probiotic for shrimps, exhibiting positive impacts on growth performance and immune response [100]. This also includes minimising disease recurrence and increasing the enzymatic activities associated with feed ingestion, growth, and shrimp survival (Figure 2) [101].

A comprehensive evaluation of *Bacillus coagulans* and *Bacillus firmus*, in both live and lyophilised forms, revealed significant improvements in growth parameters, including weight gain, length increase, and specific growth rate (SGR), when these probiotics were administered either independently or in combination with spirulina and yeast. Notably, the combined probiotic diet also led to improved survival rates and feed conversion ratios (FCR) [102]. Further investigation isolated *Bacillus subtilis* and *Bacillus licheniformis* from *Penaeus monodon*, demonstrating that their inclusion in the diet significantly increased the activities of digestive enzymes, such as protease, amylase, and cellulase, which indicates enhanced digestive efficiency [103]. The incorporation of hydrolysed squid by-products alongside *Bacillus subtilis* BF12 in a plant-based diet for *P. monodon* resulted in substantial improvements in growth performance, feed efficiency, nutrient retention, and immune responses. This combination not only enhanced digestive enzyme activity but also promoted beneficial gut microbiota, suggesting a multifaceted impact on shrimp health [104].

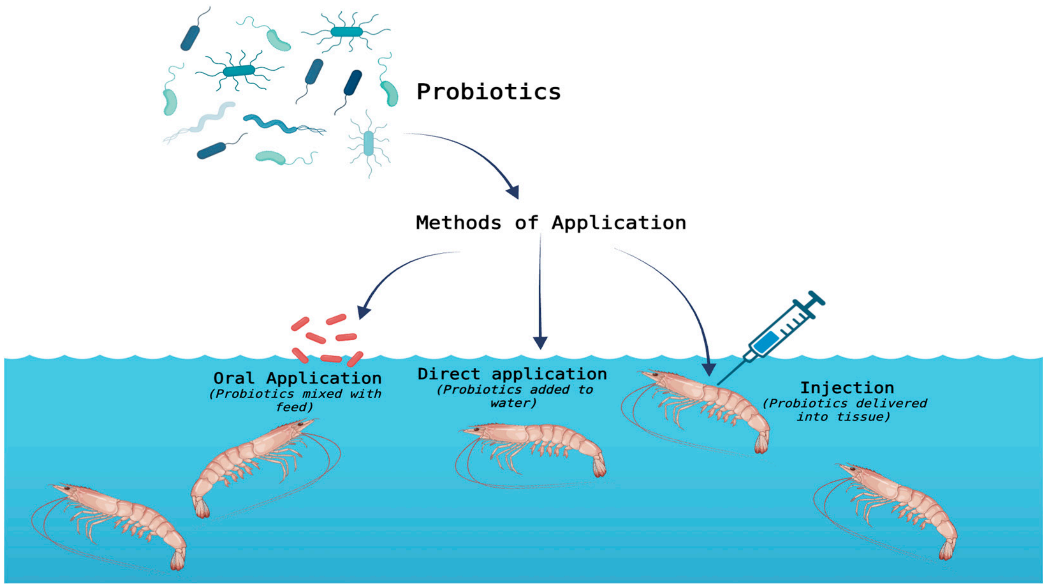

Figure 2. Methods of delivering probiotics to *Litopenaeus vannamei* shrimp. Adapted with permission from Amiin et al. [98]. Copyright 2023—under the terms of the Creative Commons Attribution 4.0 license.

A cost-effective probiotic formulation containing *Bacillus cereus* has demonstrated notable improvements in growth rates, immune parameters, and survival rates within shrimp diets [105,106]. Supplementing shrimp ponds with *Streptococcus phocae* PI80, administered through both feed and water, has been documented to significantly enhance growth and immune responses while reducing the prevalence of pathogenic bacteria [107]. Similarly, the incorporation of *Clostridium butyricum* into shrimp diets has been shown to enhance growth, increase digestive enzyme activity, and strengthen antioxidant defences, all of which contribute to increased resilience against nitrite stress [108]. Moreover, the application of *Bacillus* sp. Mk22 has shown dual benefits by promoting growth and survival while simultaneously reducing infections associated with *Vibrio* spp. and white spot syndrome virus (WSSV), highlighting its potential in disease management strategies [109]. Finally, the *Bacillus* isolate P11, identified as *Bacillus subtilis*, has demonstrated improved growth performance, feed efficiency, and an enhanced immune response against *Vibrio harveyi*, thus underscoring its effectiveness as a probiotic agent [110].

These studies have shown that when used as dietary supplements, probiotics enhance the competitive elimination of pathogens from aquaculture systems and improve the shrimp's immunological parameters. Thus, probiotics serve as a sustainable alternative to antibiotics with enhanced environmental protection and stability. However, there are some constraints to their use in shrimp aquaculture due to their expense, which leads to high production costs and complications in administering precise probiotics as dietary additives [111]. Table 2 summarises the constraints and potentials of probiotics, prebiotics, and synbiotics in shrimp aquaculture.

Table 2. Constraints and potentials of probiotics, prebiotics, and symbiotics in shrimp aquaculture.

Potentials	Constraints	References
	PROBIOTICS	
Improve gut health and nutrient uptake.	Challenges in strain selection and dosage optimisation.	[112–114]
Enhance disease resistance, immune response, and the secretion of antibacterial compounds and antitoxins.	Environmental conditions impacting efficacy.	[112–116]
Maintain a balanced microbial community in ponds.	An overdose can cause immunosuppression.	[112,113,117]
Reduce pathogen levels and enhance water quality.	There is limited understanding of mechanisms in aquaculture systems.	[112–115,117]
Enhance feed efficiency, stimulate digestive enzyme activity, and promote growth and reproduction.	Storage and maintenance of live cultures.	[118,119]
Regulate the immune system and manage allergic responses.	Potential environmental incompatibility with aquatic hosts.	[112,116,120]
	PREBIOTICS	
Improve water quality and decrease pollution.	Limited research on specific prebiotic effects in shrimp.	[121,122]
Enhance growth and survival rates, increase stress resistance and health status, and modulate enteric microbiota and immune responses.	There is a need for further studies to understand the molecular impacts.	[121,122]
	SYMBIOTICS	
Combine the benefits of probiotics and prebiotics.	Complexity in formulation and application.	[123,124]
Improve metabolic pathways and energy metabolism, boost growth performance and immune function, and decrease the severity of infections, thereby raising survival rates.	There is a need for more research on specific symbiotic combinations.	[123–125]

3.3. Growth Response of Fish to Probiotics and Prebiotics as Feed Additives

According to the Food and Agriculture Organization (FAO), probiotics are live microbial feed supplements that confer health benefits to the host by modifying the gastrointestinal microbial community [111,126]. Conversely, prebiotics are non-digestible feed additives that stimulate the activity of beneficial gut microorganisms [111,127]. Probiotics produce beneficial enzymes that facilitate digestion and safeguard the gastrointestinal tract in fish [128,129]. Additionally, they enhance the balance of intestinal microbes, resulting in increased digestive enzyme activity, improved nutrient absorption, and decreased pathogenic issues within the gastrointestinal tract when administered at appropriate dosages [130]. Probiotics function synergistically with digestive enzymes in the fish gastrointestinal tract, serving as supplements to optimise nutrition [131]. Consequently, fish feed efficiency and growth rates are augmented, while also preventing antinutritional factors in ingredients, reducing intestinal disorders, and aiding pre-digestion [129].

In Atlantic salmon (*Salmo salar*), the addition of mannanoligosaccharide, fructooligosaccharide, and galactooligosaccharide at 10 g kg^{-1} of prebiotics to a fish meal-based diet did not impact growth and digestibility. This finding suggests that adding prebiotics at a particular concentration may not enhance growth or digestive efficacy. In other studies, a diet containing 2 g kg^{-1} mannanoligosaccharide has been shown to improve fish growth, feed efficiency, and survival rates compared to those fed the basal diet [132,133]. These findings highlight the superior growth performance of mannanoligosaccharide compared to other prebiotics, such as fructooligosaccharide and galactooligosaccharide [58,91,134].

The consequences of prebiotic intake extend beyond typical biological networks, influencing the composition of fish gut microbiota; they also actively participate in this process [135]. The process goes both ways, as diverse materials present within the gut can affect microbial communities while simultaneously affecting those components directly or indirectly [119]. By feeding prebiotic oligosaccharides, such as inulin and oligofructose, populations of beneficial bacteria can be initiated, enhancing gut performance while eliminating harmful bacterial competition, as they find these substrates unsuitable [136].

Similarly, prebiotics promote the growth of beneficial bacteria without undergoing digestion [137]. By facilitating the proliferation of these microorganisms within aquatic fauna, it becomes feasible to sustain optimal gastrointestinal conditions across various fish species without dependence on costly or complex treatments typically associated with conventional methods [138]. Beneficial microorganisms flourish in environments with proper nutrition, which stimulates their growth and activity [131]. Prebiotics demonstrate a remarkable potential to uphold optimal fish health by modulating gut microbiota balance, enhancing nutrient utilisation, and promoting gastrointestinal health [139].

4. Feed Additives in Fish and Shrimp Diets

Feed additives are widely used in fish and shrimp diets to enhance growth performance, feed efficiency, and overall health [140]. These additives are specifically formulated to provide essential nutrients, vitamins, and minerals that may be deficient in conventional feed ingredients. They can be utilised to reduce the costs associated with specialized feeds (e.g., soybean meal and rice bran in fish feed pellets) and to improve the feed's taste and appeal, making it more palatable to fish and shrimp. Table 3 provides an overview of various feed additives used in fish and shrimp aquaculture, along with their respective dosages.

Table 3. Different types of synthetic feed additives in fish and shrimp diets.

Feed Additives	Function	Fish Species	Dosage Recommendation	Environmental Risk	References
Antibiotics	Growth and feed efficiency, reduced disease occurrence	Various fish species, shrimp	Varies with antibiotic type	High risk	[141]
Astaxanthin	Pigmentation, growth, and antioxidant	Atlantic salmon (*Salmo salar*), Rainbow trout (*Oncorhynchus mykiss*), Discus fish (*Symphysodon* spp.).	50–100 mg kg^{-1} of feed	Limited information, but likely biodegradable	[142,143]
Beta-carotene	Pigmentation, growth, and antioxidant	Nile tilapia (*Oreochromis niloticus*), African catfish (*Clarias gariepinus*), shrimp	50–100 mg kg^{-1} of feed	Limited information, but likely biodegradable	[142]
Betaine	Osmoregulation, nutrient utilisation, and stress resistance	Barramundi (*Lates calcarifer*), prawn	500–1000 mg kg^{-1} of feed	Limited information, but likely biodegradable	[144]
Butylated Hydroxytoluene (BHT)	Preservative	Channel catfish (*Ictalurus punctatus*), lobster (*Homarus gammarus*)	50–100 mg kg^{-1} of feed	Potential risk due to low biodegradability	[143]

Table 3. *Cont.*

Feed Additives	Function	Fish Species	Dosage Recommendation	Environmental Risk	References
Choline Chloride	Growth promoter	Various fish species, shrimp	500–1000 mg kg^{-1} of feed	Limited information, but likely biodegradable	[5]
Enzymes (e.g., Phytase)	Digestive enhancer	Various fish species, shrimp	As per the enzyme activity levels	Generally considered safe	[5,145]
Ethoxyquin	Antioxidant	Rainbow trout (*Oncorhynchus mykiss*), crab (*Brachyura* spp.)	100–200 mg kg^{-1} of feed	Potential risk due to low biodegradability	[146,147]
Mould Inhibitors (e.g., Propionic Acid)	Antifungal agent	Various species	2–4 g kg^{-1} of feed	Limited information, but likely biodegradable	[148,149]
Sodium Bicarbonate	pH regulator	Carp (*Cyprinus carpio*), shrimp	1–2 g kg^{-1} of feed	Limited information, but likely biodegradable	[150,151]
Synthetic Arginine	Amino acid supplement	Atlantic salmon (*Salmo salar*), Rainbow trout (*Oncorhynchus mykiss*), African catfish (*Clarias gariepinus*), shrimp	Varies with species	Limited information, but likely biodegradable	[46,152]
Synthetic Lysine	Amino acid supplement	Nile tilapia (*Oreochromis niloticus*), African catfish (*Clarias gariepinus*), shrimp	Varies with species	Limited information, but likely biodegradable	[153]
Synthetic Methionine	Amino acid supplement	Various fish species, shrimp	2–4 g kg^{-1} of feed	Limited information, but likely biodegradable	[154]
Synthetic Phospholipids	Emulsifiers, chemoattraction	Various fish species, shrimp	-	Limited information, but likely biodegradable	[155]
Synthetic Taurine	Cellular and physiological processes	Atlantic salmon (*Salmo salar*), Rainbow trout (*Oncorhynchus mykiss*), African catfish (*Clarias gariepinus*),	-	Limited information, but likely biodegradable	[156,157]
Vitamin C	Immune booster, antioxidant, and stress resistance	Various fish species, shrimp	100–300 mg kg^{-1} of feed	Generally considered safe	[158,159]

5. Phytogenics as Feed Additives in Fish and Shrimp Diets

Phytogenics, a novel category of feed additives, are increasingly attracting attention in the aquaculture sector [160]. Phytogenics offer several advantages as feed additives for aquatic animals, such as the potential to enhance feed digestibility, particularly with proteins and amino acids [161] (Table 4). Phytogenic feed additives (PFAs) are plant-derived substances incorporated into animal feed to enhance their performance. In aquatic feeds, aromatic plant essential oil-based feed additives are widely used as the predominant type of phytogenic product due to their antimicrobial and antioxidant properties, stability, ease of formulation, and regulatory acceptance in many regions [9,162,163].

Growing evidence supports the potential benefits of phytogenics in aquaculture, particularly for species such as fish and shrimp [9,164]. Phytogenic feed additives have been shown to positively impact the growth and health of fish and shrimp [165]. Fish and shrimp fed diets containing phytogenics experienced improved feed conversion, enhanced growth, and increased innate immunity factors [166]. *Phyllanthus niruri* leaf extracts enhanced specific and non-specific immune responses in Mozambique tilapia (*Oreochromis mossambicus*) [167]. The extract also enhanced the growth performance of the fish through enzymatic and antibody-mediated mechanisms.

Dietary supplementation with white mustard (*Sinapis alba*) seed oil at concentrations of 0.5%, 1% and 1.5% for 42–63 days significantly enhanced growth performance in rainbow trout (*Oncorhynchus mykiss*), with the 1.5% inclusion level yielding the most significant growth response [168]. The use of extracts from plants such as *Aegle marmelos*, *Cynodon dactylon*, *Withania somnifera* (ashwagandha or winter cherry), and *Zingiber officinale* (ginger), as feed additives, also improved feed efficiency and growth performance in *Oreochromis mossambicus* [169]. Table 4 summarizes the benefits of different phytogenic compounds in aquaculture.

Table 4. Phytogenics as feed additives in aquaculture.

Phytogenic Compounds	Benefit	Description	References
Ginger, oregano, thyme, garlic	Growth promotion	Enhances feed intake and digestion, leading to improved growth performance	[170,171]
Carvacrol, thymol	Antimicrobial activity, growth promotion	Inhibits pathogenic bacteria and fungi in the gut	[172]
Echinacea, garlic, turmeric	Immune system enhancement	Stimulates innate immune responses and disease resistance	[173]
Curcumin, flavonoids, polyphenols	Antioxidant properties, disease resistance, reproductive, and growth performance	Reduces oxidative stress and improves cellular health, survival, and growth	[174]
Fennel and anise essential oils	Antibacterial, antioxidant, growth performance, lipid metabolism	Enhanced growth performance and well-being	[175,176]
Liquorice	Antioxidant properties, disease-resistant, immunostimulant	Enhances growth and survival, reduces oxidative stress	[177]
Herbal blends	immune responses, antioxidants, and disease resistance	Enhanced growth and survival	[178]

Further studies have demonstrated that phytogenic additives can positively impact fish growth, although their mechanisms and effectiveness vary widely. For example, *Zingiber officinale* (ginger) has been shown to enhance the growth of African catfish (*Clarias gariepinus*), as reflected by growth metrics such as weight gain, specific growth rate, and protein efficiency ratio [179,180], with 20% supplementation producing the most notable growth increase. Including 20% as a supplement may not be economically feasible for commercial feed production compared to traditional additives, due to the high cost. However, lower supplementation levels (2–3%) have been shown to significantly improve growth performance and health metrics, offering a more cost-effective solution [181,182]. Therefore, it is recommended to use ginger at these lower levels to achieve economic and health benefits in commercial aquaculture operations. While feed additives have demonstrated benefits for growth, feed efficiency, and disease resistance, their adoption in commercial aquaculture largely depends on considerations of cost-effectiveness and environmental sustainability. For example, in fish, the inclusion levels of phytogenic additives must be economical relative to traditional feeds, and their uptake is influenced by ingredient availability and regional market dynamics [179,180]. Moreover, some additives raise environmental concerns; antibiotic-based additives, in particular, have been linked to antimicrobial resistance in intensive aquaculture, highlighting the necessity for safer alternatives [17,18]. Even natural compounds and innovative delivery methods encounter challenges such as variable efficacy under different conditions or the potential accumulation of residues in the environment. Conversely, *Aloe vera* crude polysaccharide extracts have also been found to improve growth performance and protein efficiency ratio in the same species, even at much lower levels (0.5–4.0%) [183], suggesting that certain phytogenics may be effective at lower, more cost-effective doses.

Moreover, a study on channel catfish (*Ictalurus punctatus*) demonstrated that including matrix-encapsulated phytogenics in their diets improved weight gain and reduced the feed conversion ratio, providing practical alternatives for improving feed efficiency for feed manufacturers [161]. Garlic–cinnamon blends have also been shown to enhance the immune response and overall well-being in shrimp [184]. Supplementing the diet of striped catfish (*Pangasianodon hypophthalmus*) with different cinnamon products increased the specific growth rate and protein retention [185]. Carvacrol supplementation has also resulted in significant improvements in the growth performance of Nile tilapia (*Oreochromis niloticus*) [186], emphasizing that the effectiveness and function of phytogenic additives may be species-specific.

These studies highlight the importance of PFAs in aquafeed and their potential to enhance growth performance and overall health in fish and shrimp. They also suggest that adding phytogenics as feed additives to fish and shrimp diets could reduce reliance on fish meal as a feed ingredient, potentially leading to a more sustainable and cost-effective approach [187–189]. However, the effectiveness of these extracts may vary depending on the plant type, the extraction method used, and the concentration of the extract [9].

5.1. Emerging and Next-Generation Feed Additives in Aquaculture

In addition to conventional immunostimulants and probiotics, recent years have seen the emergence of innovative additives and engineered methodologies aimed at enhancing the specificity, stability, and sustainability of health interventions in aquaculture. These advanced, next-generation feed additives are designed to enhance animal health and productivity while addressing issues related to antibiotic resistance. The developments encompass bacteriophage–probiotic combinations, postbiotics, nano- and micro-encapsulation techniques for targeted delivery, and the development of engineered microbial strains.

Bacteriophage therapy has demonstrated considerable potential in reducing pathogen carriage within animals, particularly when administered immediately prior to slaughter to target "super-shedders" [190]. However, the transient nature of bacteriophages and the possibility of phage-resistant subpopulations necessitate meticulous application. Conversely, multi-species probiotics are increasingly employed in aquaculture to enhance the health, growth, and disease resistance of aquatic organisms [191,192]. They operate through mechanisms such as competitive exclusion of pathogens and stimulation of the host immune system, thereby rendering them more effective than single-strain probiotics [193,194]. Thus, their application can be facilitated via various methods, primarily as feed additives. A summary of the comparative advantages and limitations of conventional and emerging feed additives in aquaculture is presented in Table 5.

Table 5. Comparative overview of emerging and conventional feed additives in aquaculture.

Additive	Main Action	Advantages	Limitations and Risks	Cost-Effectiveness	Environmental Impact	Reference
Conventional probiotics	Microbiome modulation, competitive exclusion	Widely available, several validated strains	Strain survival, variable effects	Moderate	Low–moderate	[195]
Bacteriophage–probiotic	Targeted pathogen lysis	Antibiotic alternative; specificity	Host range, regulatory, and environmental concerns	Moderate–high	Low–moderate	[196]
Nano-encapsulated phytogenics	Protected delivery, controlled release	Lower dose, improved bioavailability	Cost and potential nano-ecotoxicity	Moderate–high	Potential accumulation risk	[197]
Engineered/CRISPR probiotics	Precision metabolic modulation	High specificity potential	Genetically modified organism regulation; public acceptance	Currently high	Unknown	[198]
Postbiotics	Bioactive metabolites, immune modulation	Storage stability, no live microbes	Need to identify active compounds	High	Low	[199]
Synbiotics/microencapsulated probiotics	Enhanced survival + prebiotic support	Improved stability and colonisation	Cost, formulation complexity	High	Moderate	[197,200]

Postbiotics, comprising preparations of inanimate microorganisms and their constituents, confer health benefits while circumventing the risks associated with live probiotics. They have the capacity to improve gastrointestinal health, decrease inflammation, and exhibit antimicrobial properties [201,202]. The potential applications of postbiotics are presently being investigated within the scope of active food packaging to prolong shelf life and serve as bio-preservatives, thereby demonstrating their adaptability in both animal health and food safety sectors [203].

Innovative encapsulation methods, including hydrogels, electrospinning, and 3D bioprinting, are being developed to enhance the delivery and viability of probiotics and postbiotics [204]. These nano- and micro-encapsulation technologies serve to protect active ingredients from adverse environmental conditions and facilitate their targeted delivery within the gastrointestinal tract [204]. By ensuring the probiotics reach the intestinal environment in an active state, encapsulation can markedly enhance their stability and functional efficacy.

Engineered microbial strains, including next-generation probiotics (NGPs) and CRISPR-edited strains, represent a significant advancement in the field of feed additives [205]. Next-generation probiotics (NGPs), such as *Akkermansia muciniphila* and *Bacteroides* spp., are being developed to confer specific health benefits, including modulation of gut microbiota, reduction of inflammation, and enhancement of metabolic health [206,207]. These strains require more nutritional resources and exhibit increased sensitivity to aerobic conditions, thereby necessitating the implementation of sophisticated delivery systems [208]. Furthermore, engineered strains, such as *Lactobacillus plantarum* engineered to express antimicrobial peptides, demonstrate considerable potential in improving disease resistance and growth performance in aquaculture, through the targeted expression of beneficial compounds [205].

For industry adoption, evaluations of new additives must address key factors: (1) effectiveness and reproducibility across species and scales, as laboratory results may not translate to cages or ponds; (2) a cost–benefit analysis covering production, storage, and administration costs, as well as benefits like improved growth or lower mortality; (3) supply chain and availability for producers in low- and middle-income countries; (4) regulatory approval and consumer acceptance, especially for options like phages, nanoparticles, and genetically modified microbes; (5) ecological risks and residue concerns, such as phage persistence, nanoparticle buildup, and antibiotic-resistance gene mobilization. While current research is promising, few studies combine biological effectiveness with economic and environmental assessments. Addressing this gap should be a focus for future trials and evaluations.

5.2. Mechanisms of Action and Measurable Biomarkers

Natural immunostimulants, particularly beta-glucans and nucleotides, play a pivotal role in enhancing the immune response of fish. Beta-glucans, which are polysaccharides derived from yeast and fungi, activate the innate immune system by binding to specific receptors on immune cells, such as macrophages and neutrophils. This interaction triggers a cascade of immune responses, including increased phagocytic activity and the production of reactive oxygen species, which are crucial for combating pathogens [30,209]. Furthermore, beta-glucans have been shown to upregulate the expression of cytokines, such as interleukin-1β and interleukin-10, thereby modulating the immune response and enhancing the fish's ability to resist infections [210–212]. This immunomodulatory effect not only improves disease resistance but also contributes to overall growth performance by reducing the energy expenditure associated with immune challenges.

Nucleotides, on the other hand, serve as essential building blocks for nucleic acids and play a critical role in cellular metabolism and energy transfer. Their supplementation in fish diets has been linked to improved gut health and enhanced growth performance [213–215]. Nucleotides can stimulate the proliferation of intestinal epithelial cells, thereby improving gut integrity and nutrient absorption. They have been shown to modulate the gut microbiota, promoting a favourable microbial balance that supports digestion and immune function [216,217]. The synergistic effects of beta-glucans and nucleotides underscore the importance of a comprehensive approach to immunostimulation in aquaculture, where enhancing both innate immunity and gut health can lead to substantial improvements in fish growth and resilience (Figure 3).

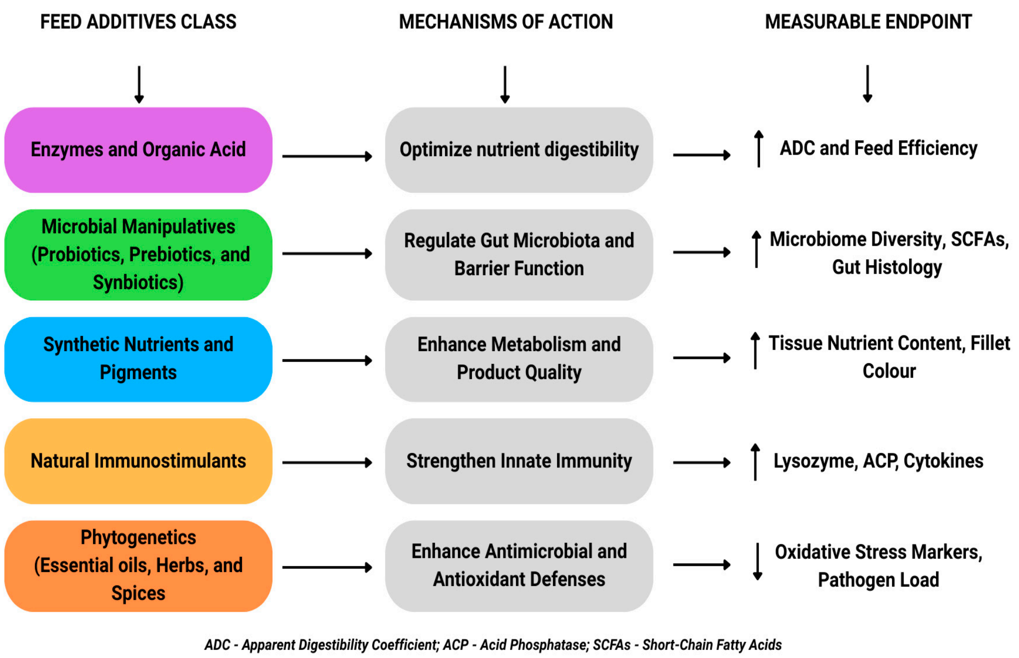

Figure 3. Mechanisms of action and measurable endpoints for feed additives in aquaculture.

Probiotics enhance nutrient utilisation and improve growth performance by increasing digestive enzyme activity and promoting a balanced gut microbiome [218,219]. The presence of probiotics in the gastrointestinal tract can inhibit the growth of pathogenic bacteria through competitive exclusion and the production of antimicrobial substances [220,221].

This not only improves the overall health of the fish but also reduces the incidence of disease, thereby minimising the need for antibiotic interventions. Prebiotics, on the other hand, selectively stimulate the growth of beneficial gut bacteria, complementing the effects of probiotics by fostering a healthy microbial environment [222,223]. The fermentation of prebiotics in the gut results in the production of short-chain fatty acids (SCFAs), which serve as an energy source for intestinal cells and exhibit anti-inflammatory properties [223,224]. Thus, the combined use of probiotics and prebiotics can significantly enhance the gut health of fish, leading to improved feed conversion ratios and growth rates. This microbiome modulation is particularly significant in aquaculture, where the stress of farming conditions can disrupt the natural balance of gut microbiota, resulting in health issues and reduced growth.

Phytogenics enhance the immune response in aquaculture species by modulating cytokine production and activating immune-related genes [225–227]. They possess antimicrobial properties that help control bacterial and parasitic infections by penetrating microbial cells and causing dysfunction [227,228]. These compounds reduce oxidative stress through their antioxidant activity, upregulating antioxidant enzymes to protect tissues from damage [229,230]. Phytogenics facilitate growth by enhancing digestive enzyme activity and nutrient absorption, thereby improving feed conversion ratios [225,229]. They additionally demonstrate anti-inflammatory properties through the downregulation of pro-inflammatory cytokines, contributing to overall health and resilience against disease [227,229,230]. Furthermore, phytogenics may influence reproductive performance through interactions with hormone receptors and modulation of hormone levels, thereby improving gonadal development and sperm quality [230].

Enzymes in aquaculture enhance protein digestibility and nutrient utilisation by breaking down proteins into smaller peptides and amino acids, facilitating better absorption [231,232]. They also improve gut health and immune response, contributing to overall fish health and reducing waste, which benefits water quality [231,232]. Organic acids primarily operate through their antimicrobial effects, suppressing the proliferation of detrimental bacteria within the digestive system and reducing stomach pH levels to augment the activity of digestive enzymes [233,234]. This facilitates improved nutrient absorption and enhances growth performance.

6. Environmental Concerns About Aquatic Feed Additives

Concerns about the environmental effects of fish and shrimp farming relate to the improper use of feed additives. Although these additives offer certain benefits, their misuse and improper disposal can lead to adverse environmental impacts [235]. For instance, the improper disposal and accumulation of florfenicol in the aquatic environment have been documented with significant environmental and health implications [236,237]. Consequently, addressing these issues requires a combination of improved practices, alternative treatments, and stringent regulatory measures to ensure the sustainability and safety of aquaculture. Antibiotics or antimicrobials are commonly used feed additives to control bacterial diseases and promote growth in fish and shrimp farming [238,239]. However, their use in aquaculture and livestock farming is increasingly restricted in regions such as the European Union and the United States due to worries about antimicrobial resistance and food safety. These resistant bacteria can spread to the surrounding environment through effluent discharge, potentially contaminating water bodies and harming other organisms that interact with them [240].

Fish feed is enriched with essential nutrients, including vitamins, minerals, and amino acids, to meet the nutritional needs of farmed fish and shrimp [241]. Improper application or excessive use of supplements in aquaculture can cause nutrient buildup and eutrophication in nearby water bodies [242]. These effects include decreased oxygen levels, the death of aquatic organisms, and disruptions to the ecosystem [243].

Several measures can effectively reduce the negative environmental impacts of feed additives [244]. Implementing strategies to reduce antibiotic use in aquatic animal feed has proven highly effective [245]. This is especially important in addressing misuse and overuse in regions like Asia, the Middle East, and Africa. Promoting alternative feed additives, such as probiotics and prebiotics, which have similar benefits for animal health and growth, can help achieve this goal [246]. Overall, developing and applying effective strategies that meet both environmental and sustainable needs for using aquatic animal feed additives is crucial. These strategies should consider environmental and public health issues, necessitating collaboration among stakeholders, including farmers, researchers, and policymakers [247], while also taking economic factors into account. A summary of the impact of antibiotics used as aqua feed additives on the aquatic environment is presented in Table 6.

Table 6. Impact of antibiotics used as aquafeed additives on the aquatic environment.

Antibiotic	Environmental Impact	References
Doxycycline	- Causes a significant decrease in glycogen and protein levels in fish tissues. - Results in scale loss, mucus hypersecretion, and abnormal swimming patterns. - Concentrations above 10 mg/L raise public health concerns due to the presence of antibioticresistant genes.	[248]
Sulfonamides	- Inhibits periphyton growth and alters microbial community structure. - Increases the abundance of resistance genes (sul1 and sul2). - Causes genotoxicity and histopathological changes in aquatic organisms.	[249,250]
Florfenicol	- Detected in high concentrations in aquaculture water, posing a significant risk to algae. - Inhibits the growth of marine microalgae *Tetraselmis suecica*.	[251,252]
Oxytetracycline	- Inhibits the growth of marine microalgae *Tetraselmis suecica*. - Accumulates in sediments and nontarget organisms, impacting biodiversity.	[251,253]
Chloramphenicol	- Inhibits the growth of marine microalgae *Tetraselmis suecica*.	[251]
Enrofloxacin; Ciprofloxacin	- High transportability from plasma to muscle and liver in fish. - Detected in high concentrations in mariculture water, posing resistance risks.	[254,255]
Erythromycin	- Detected in high concentrations in mariculture water, posing resistance risks.	[252,255]

7. Regulatory Framework for the Use of Feed Additives in Fish and Shrimp Farming

Aquatic feed additives have become crucial to ensure efficient and sustainable operations within the aquaculture industry [256]. Regulatory measures and oversight are critical in ensuring that aquatic feed additives are used safely, effectively, and sustainably [257]. Such measures include monitoring and enforcing guidelines for the use of feed additives to enhance pigmentation, growth, and antioxidant function [258]. This is essential for consumer safety and the protection of the aquatic species' environment.

7.1. International Regulatory Framework

At the international level, various organizations have played a key role in establishing regulations and standards for the proper use of feed additives in aquaculture across different countries [259]. The Food and Agriculture Organization (FAO) and the World Health Organization (WHO) are well-known global bodies involved in such efforts. They jointly established the Codex Alimentarius Commission (CAC/GL 3-1989), which carefully oversees food standards, focusing on setting guidelines related to aquafeed and other feed additives [260,261]. The regulation CAC/GL 3-1989 provides a detailed method for screening and assessing dietary exposure to food additives using accessible data, including food consumption patterns and maximum permitted levels. This helps evaluate compliance with Acceptable Daily Intake values effectively and supports risk management decisions, emphasizing the need for further evaluation or monitoring of additives [260,262].

Another key regulatory authority is the World Organisation for Animal Health (OIE), which aims to strictly enforce responsible use practices within animal production systems worldwide, especially those related to aquatic animals [263]. This organization also emphasizes the importance of maintaining animals' well-being throughout their lifecycle and ensuring that production remains sustainable and within the bounds of food safety [264]. Table 7 summarizes the different regulatory aspects of aquaculture feed additives in the European Union, the United States, and China.

Table 7. A comparison of regulatory approval timelines or safety thresholds (EU vs. US vs. China) of feed additives used in aquaculture.

Aspect	European Union (EU)	United States (US)	China	Reference
Regulatory Body	- European Food Safety Authority (EFSA)	- Food and Drug Administration (FDA) and Association of American Feed Control Officials (AAFCO)	Ministry of Agriculture and Rural Affairs (MARA)	[265–267]
Approval Process	- Comprehensive assessment of safety for animals, consumers, the environment, and handlers - Compulsory authorization for all additives - Guidance documents provided by EFSA	- FDA and AAFCO regulate safety and efficacy - Approval based on scientific evidence and safety data	- Proactive government policies - Focus on reducing feed cost and waste discharge	[265–271]
Safety Thresholds	- Specific safety assessments for each additive - Acceptable Daily Intake (ADI) levels are defined for certain additives	- Safety and efficacy must be demonstrated - Specific safety thresholds for additives like acetic acid	- Emphasis on accurate nutrient supply and reducing toxicity	[265,266,269, 271–273]
Legislation	- Regulation (EC) No 1831/2003 - Food Improvement Agent Package (FIAP) - REFIT program for evaluating legislation	- Federal Food, Drug, and Cosmetic Act (FFDCA) - Specific regulations for genetically engineered animals	- Policies for sustainable development and food safety	[265,268,270, 274–276]
Focus Areas	- Safety for target animals, consumers, the environment, and handlers - Efficacy of additives	- Safety and efficacy for animal health and productivity - Environmental impact assessments for GE animals	- Reducing feed cost and waste discharge - Ensuring food safety	[265,269–271,274]
Challenges	- Ambiguities in guidance documents - Need for better endpoints for data collection	- Concerns about the adequacy of regulatory safeguards for GE animals	- Coordination among governmental organizations - Ensuring compliance with regulations	[270,274]

7.2. Regional and National Regulatory Frameworks

The rules for incorporating feed additives in aquaculture vary significantly by region or country [263]. For instance, Regulation (EC) No. 1831/2003 oversees the management of nutritional supplements within the European Union (EU) territories, covering everything from authorization and product labelling to distribution through marketing channels [277]. Whenever a new feed additive enters the EU market, it undergoes a thorough evaluation by the European Food Safety Authority (EFSA) before approval; safety requirements also extend to post-approval issues like environmental impact and human safety, making sure no adverse effects occur once it is approved and distributed across various markets [278].

In the United States, regulations regarding feed supplements are overseen by the Food and Drug Administration (FDA), which operates under the authority of the Federal Food, Drug, and Cosmetic Act. The Association of American Feed Control Officials (AAFCO) guides each state in regulating its respective feed supplements [279]. Among other responsibilities, the FDA regulates finished dietary supplement products and dietary ingredients under rules that are different from those governing "conventional" foods and drug products [280]. The FDA also enforces a mandatory safety program for fish and fishery products, and manufacturers of dietary supplements must follow current good manufacturing practices [281].

Furthermore, in China, the Ministry of Agriculture of the State Council, now called the Ministry of Agriculture and Rural Affairs, oversees the regulation of national feed and feed additive administration. It manages the classification and approval of feed additives in accordance with the outlined legislation. At the local level, this responsibility falls to the relevant administrative departments under county governments [282].

While each country has its standards for feed supplements in the global aquaculture industry, countries in the European Union follow a unified legal framework that supports intra-EU trade. Regardless of jurisdiction, assessing the safety, potential risks, and overall effectiveness of an additive remains a key part of regulatory oversight [283]. During the approval process, scientific committees from leading regulatory agencies review 'dossiers,' which include scientific data, toxicological information, and detailed environmental risk assessments of the additives before approval.

8. Key Issues and Measurable Endpoints in the Application of Feed Additives

The practical application of feed additives in aquaculture is associated with several key issues that must be addressed to ensure their sustainable use. These include variability in additive efficacy across species and environments, inconsistent quality and availability, potential adverse effects on fish physiology, consumer safety concerns regarding residues, and ecological impacts such as antimicrobial resistance or nutrient loading.

To evaluate these challenges systematically and comparably, future studies should adopt standardized, measurable endpoints. Core growth and production metrics include feed conversion ratio (FCR), specific growth rate (SGR), protein efficiency ratio (PER), and survival rate. Health and welfare indicators encompass haematological and biochemical profiles, innate immune markers (e.g., lysozyme, complement, phagocytic activity, phenoloxidase), gut histomorphology, and stress enzyme activities (e.g., superoxide dismutase (SOD), catalase (CAT), malondialdehyde (MDA)). Environmental endpoints should encompass residue accumulation in water and sediments, shifts in microbial community composition, and quantification of antibiotic resistance genes (ARGs) in effluents. Economic outcomes, such as the incremental cost per ton of feed and the return on investment per kilogram of biomass produced, should also be consistently reported.

Integrating these measurable endpoints across trials will facilitate comparability, facilitate meta-analyses, and ultimately inform evidence-based policy on additive use in aquaculture (Table 8).

Table 8. Recommended endpoints and standard assays for feed additive trials.

Parameters	Why	Assays	When
Growth and performance	Primary production metric	WG, SGR, FCR, PER	Weekly or biweekly during trials (typical 4–12 week trials)
Survival and disease resistance	Real-world production viability	Cumulative survival, post-challenge survival curves; challenge tests with common pathogens	End of trial + challenge follow-up
Innate immunity	Mechanism and prophylactic value	Serum lysozyme activity, alternative complement (ACP), phagocytic activity, respiratory burst, SOD, and CAT	Baseline, mid-trial, end-trial, and post-challenge
Adaptive immunity	Longer-term protection	Specific antibody titres, lymphocyte proliferation, and cytokine gene expression	Later timepoints (weeks) and post-vaccination/challenge
Gut health and microbiome	Central to nutrient uptake and immunity	Intestinal histology, digestive enzyme activities, 16S rRNA gene sequencing (alpha/beta diversity), SCFA quantification	Mid and end trial
Digestibility and nutrient retention	Feed efficiency and waste output	Apparent digestibility coefficients (ADC), nutrient retention indices, and faecal nutrient analysis	Final phase ± periodic sampling
Oxidative stress and tissue health	Phytogenic and antioxidant effects	SOD, MDA, CAT in liver/muscle; histopathology	End trial
Residues and environmental fate	Public health and environmental risk (esp. antibiotics, antioxidants)	Antibiotic residues in tissue/water/sediment; ARGs (qPCR); chemical residuals (LC-MS)	During and after the feeding period, sediment sampling for benthic accumulation
Product quality and composition	Market value	Fillet colour, lipid profile, proximate composition	Harvest
Environmental metrics	eutrophication/ecosystem impact	Dissolved inorganic nitrogen and phosphorus, chlorophyll a, BOD, and benthic oxygen demand	Regular pond/pen/effluent monitoring
Economics/LCA	Adoption decisions	Cost per kg gain, feed cost ratio, basic LCA endpoints if available	End of trial and scenario modelling

Legend: Weight gain (WG), Specific Growth Rate (SGR), Feed Conversion Ratio (FCR), Protein Efficiency Ratio (PER), Life cycle assessment (LCA), Short-Chain Fatty Acids (SCFA), Biochemical Oxygen Demand (BOD).

9. Knowledge Gaps and Research Priorities

Our review identifies several gaps: (1) a deficiency in long-term and field-scale research concerning ecological fate and accumulation, as most studies are limited to short laboratory experiments or small pond trials; (2) an absence of systematic studies on additive–additive and additive–ingredient interactions that could reveal synergy or antagonism; (3) inadequate dose–response data for many commercially relevant species on a species-specific basis; (4) a paucity of mechanistic studies linking additive application to molecular pathways, such as those employing omics approaches; and (5) regional disparities in regulation and enforcement that impede harmonised efforts and recommendations. It is therefore recommended to prioritise (i) standardised, multi-site dose–response trials with agreed endpoints; (ii) integrative mechanistic studies (transcriptomics, metabolomics, microbiomics) to establish modes of action and biomarkers of efficacy; (iii) long-term ecotoxicology and residue studies (water, sediment, non-target organisms); (iv) economic and life-cycle assessments for promising additives; (v) development of harmonised, evidence-based guidance documents and registries of authorised additives with species-specific dose ranges.

10. Conclusions and Future Outlook

Fish feed additives provide numerous benefits in aquaculture, including promoting growth, controlling diseases, and enhancing nutritional value. Natural immunostimulants have shown great potential as feed additives, boosting disease resistance and improving the innate immune response in fish and shrimp. Probiotics and prebiotics also have positive effects on the health of fish and shrimp in aquaculture. Synthetic feed additives provide a well-balanced diet tailored to meet the specific nutritional needs of various fish and shrimp species. These meals supply targeted nutrition to support the health of aquatic animals. However, the unregulated or improper use of these additives can lead to harmful environmental effects. Therefore, responsible use of aquatic feed additives should be a priority in sustainable aquaculture practices. This includes promoting environmentally friendly alternatives and protecting the long-term health of aquatic ecosystems.

Given the increasing interest in sustainable and eco-friendly practices, future research may explore innovative feed additives derived from natural sources, such as plant extracts, prebiotics, probiotics, and synbiotics. Studying their effectiveness, safety, and mechanisms of action can offer alternatives to traditional feed additives, thereby decreasing reliance on synthetic compounds (Figure 4). Researchers might focus on enhancing nutrient utilisation and minimising waste in aquaculture systems. This could involve examining how feed additives affect nutrient digestion, absorption, and retention, as well as their impact on waste composition and nutrient excretion. The goal is to optimise feed formulas and feeding strategies for improved efficiency and reduced environmental impact.

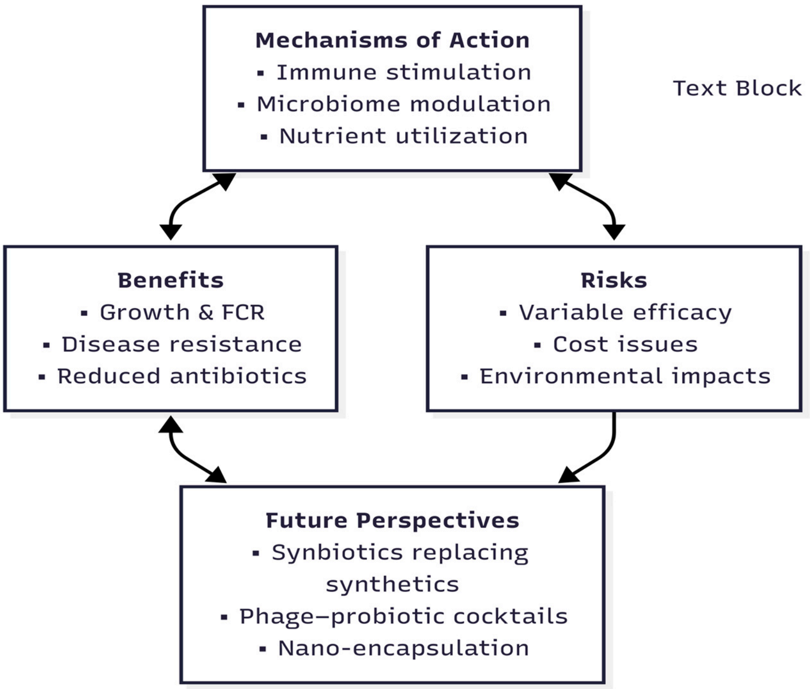

Figure 4. Schematic summary of feed additive mechanisms, benefits, risks, and future perspectives in aquaculture.

This review highlights new opportunities, but advancing requires a shift from broad speculation to targeted, empirical research. Future studies should test hypotheses supporting the use of sustainable feed additives in aquaculture. By 2030, well-developed symbiotic formulations could reduce synthetic additives by over 50% without compromising growth or survival, as confirmed through controlled farm trials that evaluated growth, immune markers, microbiome, and costs. Bacteriophage–probiotic combinations are expected to reduce *Vibrio* and *Aeromonas* infections by at least 40% and lower antibiotic resistance genes in effluent by 1 log10, as validated through farm studies on outbreaks, survival, antibiotic use, and resistance profiles. Nano-encapsulated phytogenic blends may offer growth and health benefits at half the standard dose, while reducing environmental residues by at least 30%, as demonstrated in pond trials and chemical residue analyses.

Author Contributions: E.O.: Conceptualization, Writing—Original draft preparation, Writing—Reviewing and Editing, Visualization. M.I.: Writing—Original draft preparation. P.O.: Visualization, Writing—Original draft preparation, Writing—Reviewing and Editing. M.A.: Writing—Original draft preparation. N.M.: Writing—Reviewing and Editing. R.O.: Conceptualization; Writing—Reviewing and Editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Edwards, P.; Zhang, W.; Belton, B.; Little, D.C. Misunderstandings, myths and mantras in aquaculture: Its contribution to world food supplies has been systematically over reported. *Mar. Policy* **2019**, *106*, 103547. [CrossRef]
2. Kidane, D.G.; Brækkan, E.H. Global seafood demand growth differences across regions, income levels, and time. *Mar. Resour. Econ.* **2021**, *36*, 289–305. [CrossRef]
3. Food and Agriculture Organization of the United Nations. The state of world fisheries and aquaculture 2024: Blue transformation in action. In *The State of World Fisheries and Aquaculture (SOFIA)*; FAO: Rome, Italy, 2024. [CrossRef]
4. Stentiford, G.D.; Bateman, I.J.; Hinchliffe, S.J.; Bass, D.; Hartnell, R.; Santos, E.M.; Devlin, M.J.; Feist, S.W.; Taylor, N.G.H.; Verner-Jeffreys, D.W.; et al. Sustainable aquaculture through the One Health lens. *Nat. Food* **2020**, *1*, 468–474. [CrossRef]
5. Bai, S.C.; Hamidoghli, A.; Bae, J. Feed additives: An overview. In *Feed and Feeding Practices in Aquaculture*; Woodhead Publishing: Cambridge, UK, 2022; pp. 195–229. [CrossRef]
6. Tacon, A.G. Trends in global aquaculture and aquafeed production: 2000–2017. *Rev. Fish. Sci. Aquac.* **2020**, *28*, 43–56. [CrossRef]
7. Boyd, C.E.; McNevin, A.A. Overview of aquaculture feeds: Global impacts of ingredient production, manufacturing, and use. In *Feed and Feeding Practices in Aquaculture*; Woodhead Publishing: Cambridge, UK, 2022; pp. 3–28.
8. Marimuthu, V.; Shanmugam, S.; Sarawagi, A.D.; Kumar, A.; Kim, I.H.; Balasubramanian, B. A glimpse on influences of feed additives in aquaculture. *eFood* **2022**, *3*, e6. [CrossRef]
9. Encarnação, P. Functional feed additives in aquaculture feeds. In *Aquafeed Formulation*; Academic Press: Cambridge, MA, USA, 2016; pp. 217–237.
10. Goh, J.X.H.; Tan, L.T.H.; Law, J.W.F.; Ser, H.L.; Khaw, K.Y.; Letchumanan, V.; Lee, L.H.; Goh, B.H. Harnessing the potentialities of probiotics, prebiotics, synbiotics, paraprobiotics, and postbiotics for shrimp farming. *Rev. Aquac.* **2022**, *14*, 1478–1557. [CrossRef]
11. Ochoa-Romo, J.P.; Cornejo-Granados, F.; Lopez-Zavala, A.A.; Viana, M.T.; Sánchez, F.; Gallardo-Becerra, L.; Luque-Villegas, M.; Valdez-López, Y.; Sotelo-Mundo, R.R.; Cota-Huízar, A.; et al. Agavin induces beneficial microbes in the shrimp microbiota under farming conditions. *Sci. Rep.* **2022**, *12*, 1–16. [CrossRef] [PubMed]
12. Butt, U.D.; Lin, N.; Akhter, N.; Siddiqui, T.; Li, S.; Wu, B. Overview of the latest developments in the role of probiotics, prebiotics and synbiotics in shrimp aquaculture. *Fish Shellfish Immunol.* **2021**, *114*, 263–281. [CrossRef]
13. Liang, Q.; Yuan, M.; Xu, L.; Lio, E.; Zhang, F.; Mou, H.; Secundo, F. Application of enzymes as a feed additive in aquaculture. *Mar. Life Sci. Technol.* **2022**, *4*, 208–221. [CrossRef]
14. Busti, S.; Rossi, B.; Volpe, E.; Ciulli, S.; Piva, A.; D'Amico, F.; Soverini, M.; Candela, M.; Gatta, P.P.; Bonaldo, A.; et al. Effects of dietary organic acids and nature identical compounds on growth, immune parameters and gut microbiota of European sea bass. *Sci. Rep.* **2020**, *10*, 21321. [CrossRef] [PubMed]
15. EFSA Panel on Additives and Products or Substances used in Animal Feed (EFSA FEEDAP Panel); Bampidis, V.; Azimonti, G.; Bastos, M.L.; Christensen, H.; Dusemund, B.; Durjava, M.; Kouba, M.; López-Alonso, M.; Puente, S.L.; et al. Guidance on the assessment of the safety of feed additives for the environment. *EFSA J.* **2019**, *17*, e05648.
16. Pandey, A.K.; Kumar, P.; Saxena, M.J. Feed additives in animal health. *Nutraceuticals Vet. Med.* **2019**, 345–362. [CrossRef]
17. Hedberg, N.; Stenson, I.; Pettersson, M.N.; Warshan, D.; Nguyen-Kim, H.; Tedengren, M.; Kautsky, N. Antibiotic use in Vietnamese fish and lobster sea cage farms; implications for coral reefs and human health. *Aquaculture* **2018**, *495*, 366–375. [CrossRef]

18. Pham, T.T.H.; Rossi, P.; Dinh, H.D.K.; Pham, N.T.A.; Tran, P.A.; Ho, T.T.K.M.; Dinh, Q.T.; De Alencastro, L.F. Analysis of antibiotic multi-resistant bacteria and resistance genes in the effluent of an intensive shrimp farm (Long An, Vietnam). *J. Environ. Manag.* **2018**, *214*, 149–156. [CrossRef]
19. Nikitin, A.V.; Navashin, S.M. Natural immunostimulants. *Antibiotiki* **1983**, *28*, 702–716.
20. Zebeaman, M.; Tadesse, M.G.; Bachheti, R.K.; Bachheti, A.; Gebeyhu, R.; Chaubey, K.K. Plants and Plant-Derived Molecules as Natural Immunomodulators. *BioMed Res. Int.* **2023**, *2023*, 7711297. [CrossRef]
21. Pooljun, C.; Jariyapong, P.; Wongtawan, T.; Hirono, I.; Wuthisuthimethavee, S. Effect of feeding different types of β-glucans derived from two marine diatoms (*Chaetoceros muelleri* and *Thalassiosira weissflogii*) on growth performance and immunity of banana shrimp (*Penaeus merguiensis*). *Fish Shellfish Immunol.* **2022**, *130*, 512–519. [CrossRef] [PubMed]
22. Yin, M.; Zhang, Y.; Li, H. Advances in research on immunoregulation of macrophages by plant polysaccharides. *Front. Immunol.* **2019**, *10*, 145. [CrossRef] [PubMed]
23. Servin Arce, K.; de Souza Valente, C.; do Vale Pereira, G.; Shapira, B.; Davies, S.J. Modulation of the gut microbiota of Pacific white shrimp (*Penaeus vannamei* Boone, 1931) by dietary inclusion of a functional yeast cell wall-based additive. *Aquac. Nutr.* **2021**, *27*, 1114–1127. [CrossRef]
24. Mohammadi, G.; Hafezieh, M.; Karimi, A.A.; Azra, M.N.; Van Doan, H.; Tapingkae, W.; Abdelrahman, H.A.; Dawood, M.A. The synergistic effects of plant polysaccharide and Pediococcus acidilactici as a synbiotic additive on growth, antioxidant status, immune response, and resistance of Nile tilapia (*Oreochromis niloticus*) against Aeromonas hydrophila. *Fish Shellfish Immunol.* **2022**, *120*, 304–313. [CrossRef] [PubMed]
25. Mohan, K.; Ravichandran, S.; Muralisankar, T.; Uthayakumar, V.; Chandirasekar, R.; Seedevi, P.; Rajan, D.K. Potential uses of fungal polysaccharides as immunostimulants in fish and shrimp aquaculture: A review. *Aquaculture* **2019**, *500*, 250–263. [CrossRef]
26. Li, H.; Liu, Y.; Teng, Y.; Zheng, Y.; Zhang, M.; Wang, X.; Cheng, H.; Xu, J.; Chen, X.; Zhao, X.; et al. Enhancement of seaweed polysaccharides (fucoidan and laminarin) on the phagocytosis of macrophages via activation of intelectin in blunt snout bream (*Megalobrama amblycephala*). *Front. Mar. Sci.* **2023**, *10*, 1124880. [CrossRef]
27. Kim, H.S.; Hong, J.T.; Kim, Y.; Han, S.B. Stimulatory effect of β-glucans on immune cells. *Immune Netw.* **2011**, *11*, 191–195. [CrossRef] [PubMed]
28. Sahasrabudhe, N.M.; Dokter-Fokkens, J.; de Vos, P. Particulate β-glucans synergistically activate TLR4 and Dectin-1 in human dendritic cells. *Mol. Nutr. Food Res.* **2016**, *60*, 2514–2522. [CrossRef]
29. Elder, M.J.; Webster, S.J.; Chee, R.; Williams, D.L.; Hill Gaston, J.S.; Goodall, J.C. β-Glucan size controls dectin-1-mediated immune responses in human dendritic cells by regulating IL-1β production. *Front. Immunol.* **2017**, *8*, 791. [CrossRef] [PubMed]
30. Hadiuzzaman, M.; Moniruzzaman, M.; Shahjahan, M.; Bai, S.C.; Min, T.; Hossain, Z. β-Glucan: Mode of Action and Its Uses in Fish Immunomodulation. *Front. Mar. Sci.* **2022**, *9*, 905986. [CrossRef]
31. Petrie-Hanson, L.; Peterman, A.E. Trained immunity provides long-term protection against bacterial infections in channel catfish. *Pathogens* **2022**, *11*, 1140. [CrossRef]
32. Lim, J.J.; Grinstein, S.; Roth, Z. Diversity and versatility of phagocytosis: Roles in innate immunity, tissue remodeling, and homeostasis. *Front. Cell. Infect. Microbiol.* **2017**, *7*, 191. [CrossRef]
33. Stier, H.; Ebbeskotte, V.; Gruenwald, J. Immune-modulatory effects of dietary Yeast Beta-1, 3/1, 6-D-glucan. *Nutr. J.* **2014**, *13*, 38. [CrossRef]
34. Lin, S.; Pan, Y.; Luo, L.; Luo, L. Effects of dietary β-1, 3-glucan, chitosan or raffinose on the growth, innate immunity and resistance of koi (*Cyprinus carpio koi*). *Fish Shellfish Immunol.* **2011**, *31*, 788–794. [CrossRef]
35. Meena, D.K.; Das, P.; Kumar, S.; Mandal, S.C.; Prusty, A.K.; Singh, S.K.; Akhtar, M.S.; Behera, B.K.; Kumar, K.; Pal, A.K.; et al. Beta-glucan: An ideal immunostimulant in aquaculture (a review). *Fish Physiol. Biochem.* **2013**, *39*, 431–457. [CrossRef]
36. Ochoa-Álvarez, N.A.; Casillas-Hernández, R.; Magallón-Barajas, F.J.; Ramirez-Orozco, J.M.; Carbajal-Millan, E. Protector effect of beta-glucans from shrimp pond-related yeasts in *Penaeus vannamei* rearing under white spot syndrome virus presence. *Lat. Am. J. Aquat. Res.* **2021**, *49*, 18–28. [CrossRef]
37. Andrino, K.G.S.; Augusto, E.; Serrano, J.; Valeriano, L.; Corre, J. Effects of dietary nucleotides on the immune response and growth of juvenile Pacific white shrimp *Litopenaeus vannamei* (Boone, 1931). *Asian Fish. Sci.* **2012**, *25*, 180–192. [CrossRef]
38. Gil, A. Modulation of the immune response mediated by dietary nucleotides. *Eur. J. Clin. Nutr.* **2002**, *56*, S1–S4. [CrossRef] [PubMed]
39. Wei, Z.; Yi, L.; Xu, W.; Zhou, H.; Zhang, Y.; Zhang, W.; Mai, K. Effects of dietary nucleotides on growth, non-specific immune response and disease resistance of sea cucumber *Apostichopus japonicas*. *Fish Shellfish Immunol.* **2015**, *47*, 1–6. [CrossRef]
40. Xie, S.; Yin, P.; Tian, L.; Yu, Y.; Liu, Y.; Niu, J. Dietary supplementation of astaxanthin improved the growth performance, antioxidant ability and immune response of juvenile largemouth bass (*Micropterus salmoides*) fed high-fat diet. *Mar. Drugs* **2020**, *18*, 642. [CrossRef] [PubMed]

41. Hamidoghli, A.; Lee, Y.; Hwang, S.; Choi, W.; Choi, Y.H.; Bai, S.C. Evaluation of Yeast Hydrolysate in a Low-Fishmeal Diet for Whiteleg Shrimp (*Litopenaeus vannamei*). *Animals* **2023**, *13*, 1877. [CrossRef]
42. Elumalai, P.; Kurian, A.; Lakshmi, S.; Faggio, C.; Esteban, M.A.; Ringø, E. Herbal immunomodulators in aquaculture. *Rev. Fish. Sci. Aquac.* **2020**, *29*, 33–57. [CrossRef]
43. Terzi, E.; Kucukkosker, B.; Bilen, S.; Kenanoglu, O.N.; Corum, O.; Özbek, M.; Parug, S.S. A novel herbal immunostimulant for rainbow trout (*Oncorhynchus mykiss*) against *Yersinia ruckeri*. *Fish Shellfish Immunol.* **2021**, *110*, 55–66. [CrossRef]
44. Akbar Ali, I.; Radhakrishnan, D.K.; Kumar, S. Immunostimulants and Their Uses in Aquaculture. In *Aquaculture Science and Engineering*; Springer Nature: Singapore, 2022; pp. 291–322.
45. Muahiddah, N.; Diamahesa, W.A. Potential use of brown algae as an immunostimulant material in the aquaculture field to increase non-specific immunity and fight disease. *J. Fish Health* **2022**, *2*, 109–115. [CrossRef]
46. Li, M.; Zhang, M.; Jiang, H.; Qin, C. Comparison of dietary arginine or/and inulin supplementation on growth, digestive ability and ammonia tolerance of juvenile yellow catfish *Pelteobagrus fulvidraco*. *Aquac. Rep.* **2023**, *30*, 101543. [CrossRef]
47. Vetvicka, V.; Vannucci, L.; Sima, P. The effects of β–glucan on fish immunity. *N. Am. J. Med. Sci.* **2013**, *5*, 580. [CrossRef]
48. Vallejos-Vidal, E.; Reyes-López, F.; Teles, M.; MacKenzie, S. The response of fish to immunostimulant diets. *Fish Shellfish Immunol.* **2016**, *56*, 34–69. [CrossRef] [PubMed]
49. Kumar, S.; Verma, A.K.; Singh, S.P.; Awasthi, A. Immunostimulants for shrimp aquaculture: Paving pathway towards shrimp sustainability. *Environ. Sci. Pollut. Res.* **2023**, *30*, 25325–25343. [CrossRef] [PubMed]
50. Smith, V.J.; Brown, J.H.; Hauton, C. Immunostimulation in crustaceans: Does it really protect against infection? *Fish Shellfish Immunol.* **2003**, *15*, 71–90. [CrossRef] [PubMed]
51. dos, S.; Filho, L.G.A.; Diniz, F.M.; Pereira, A.M. Immunostimulants derived from plants and algae to increase resistance of pacific white shrimp (*Litopenaeus vannamei*) against vibriosis. *Stud. Nat. Prod. Chem.* **2023**, *77*, 297–337.
52. Hossain, M.S.; Small, B.C.; Kumar, V.; Hardy, R. Utilisation of functional feed additives to produce cost-effective, ecofriendly aquafeeds high in plant-based ingredients. *Rev. Aquac.* **2023**, *16*, 121–153. [CrossRef]
53. Kiataramgul, A.; Maneenin, S.; Purton, S.; Areechon, N.; Hirono, I.; Brocklehurst, T.W.; Unajak, S. An oral delivery system for controlling white spot syndrome virus infection in shrimp using transgenic microalgae. *Aquaculture* **2020**, *521*, 735022. [CrossRef]
54. Mikucka, A.; Deptuła, A.; Bogiel, T.; Chmielarczyk, A.; Nurczyńska, E.; Gospodarek-Komkowska, E. Bacteraemia Caused by Probiotic Strains of *Lacticaseibacillus rhamnosus*—Case Studies Highlighting the Need for Careful Thought before Using Microbes for Health Benefits. *Pathogens* **2022**, *11*, 977. [CrossRef]
55. Kaur, G.; Kaur, P. Green tea (*Camellia sinensis*): It's promising health benefits for the welfare of humans. *J. Pharmacogn. Phytochem.* **2019**, *8*, 299–302.
56. Zaib, S.; Hayat, A.; Khan, I. Probiotics and their beneficial health effects. *Mini Rev. Med. Chem.* **2023**, *24*, 110–125. [CrossRef]
57. Miquel, S.; Martín, R.; Bridonneau, C.; Robert, V.; Sokol, H.; Bermúdez-Humarán, L.G.; Thomas, M.; Langella, P. Ecology and metabolism of the beneficial intestinal commensal bacterium *Faecalibacterium prausnitzii*. *Gut Microbes* **2014**, *5*, 146–151. [CrossRef]
58. Ren, C.; Faas, M.M.; de Vos, P. Disease managing capacities and mechanisms of host effects of lactic acid bacteria. *Crit. Rev. Food Sci. Nutr.* **2020**, *61*, 1365–1393. [CrossRef] [PubMed]
59. Yvon, S.; Schwebel, L.; Belahcen, L.; Tormo, H.; Peter, M.; Haimoud-Lekhal, D.A.; Eutamène, H.; Jard, G. Effects of thermized donkey milk with lysozyme activity on altered gut barrier in mice exposed to water-avoidance stress. *J. Dairy Sci.* **2019**, *102*, 7697–7706. [CrossRef]
60. Aji, M.B. Antimicrobial Compounds Activities of d2. 2 Biocontrol Bacteria Against Bacterial Pathogens on Shrimp and Fish In Vitro Aktifitas Senyawa Antimikroba Dari Bakteri Biokontrol d2. 2 Terhadap Bakteri PatogenPada Udang Dan Ikan Secara In Vitro. 2014. Available online: https://digilib.unila.ac.id/3667/1/ABSTRACT.pdf (accessed on 7 May 2025).
61. Kurashima, Y.; Kiyono, H. Mucosal ecological network of epithelium and immune cells for gut homeostasis and tissue healing. *Annu. Rev. Immunol.* **2017**, *35*, 119–147. [CrossRef] [PubMed]
62. Didierlaurent, A.M.; Collignon, C.; Bourguignon, P.; Wouters, S.; Fierens, K.; Fochesato, M.; Dendouga, N.; Langlet, C.; Malissen, B.; Lambrecht, B.N.; et al. Enhancement of adaptive immunity by the human vaccine adjuvant AS01 depends on activated dendritic cells. *J. Immunol.* **2014**, *193*, 1920–1930. [CrossRef]
63. Tang, H.G.; Wu, T.X.; Zhao, Z.Y.; Pan, X.D. Effects of fish protein hydrolysate on growth performance and humoral immune response in large yellow croaker (*Pseudosciaena crocea* R.). *J. Zhejiang Univ. Sci. B* **2008**, *9*, 684–690. [CrossRef] [PubMed]
64. Rahe, M.C.; Murtaugh, M.P. Mechanisms of adaptive immunity to porcine reproductive and respiratory syndrome virus. *Viruses* **2017**, *9*, 148. [CrossRef]
65. Fletcher, T.C.; Secombes, C.J. Immunology of fish. *eLS* **2015**, 1–9. [CrossRef]
66. Wang, J.; Ji, H.; Wang, S.; Liu, H.; Zhang, W.; Zhang, D.; Wang, Y. Probiotic *Lactobacillus plantarum* promotes intestinal barrier function by strengthening the epithelium and modulating gut microbiota. *Front. Microbiol.* **2018**, *9*, 1953. [CrossRef]
67. Corbel, M.J. The immune response in fish: A review. *J. Fish Biol.* **1975**, *7*, 539–563. [CrossRef]

68. Van Zijderveld, S.M.; Fonken, B.; Dijkstra, J.; Gerrits, W.J.J.; Perdok, H.B.; Fokkink, W.; Newbold, J.R. Effects of a combination of feed additives on methane production, diet digestibility, and animal performance in lactating dairy cows. *J. Dairy Sci.* **2011**, *94*, 1445–1454. [CrossRef] [PubMed]
69. Küçükyılmaz, K.; Bozkurt, M.; Çatlı, A.U.; Çınar, M.; Bİntaş, E. The effect of dietary supplementation of yeast and humate on broiler performance and some slaughter characteristics. *Ziraat Fakültesi Derg. Süleyman Demirel Üniversitesi* **2012**, *7*, 83–92.
70. Zheng, X.; Liu, B.; Wang, N.; Yang, J.; Zhou, Q.; Sun, C.; Zhao, Y. Low fish meal diet supplemented with probiotics ameliorates intestinal barrier and immunological function of *Macrobrachium rosenbergii* via the targeted modulation of gut microbes and derived secondary metabolites. *Front. Immunol.* **2022**, *13*, 1074399. [CrossRef]
71. Zakostelska, Z.; Kverka, M.; Klimesova, K.; Rossmann, P.; Mrazek, J.; Kopecny, J.; Hornova, M.; Srutkova, D.; Hudcovic, T.; Ridl, J.; et al. Lysate of probiotic *Lactobacillus casei* DN-114 001 ameliorates colitis by strengthening the gut barrier function and changing the gut microenvironment. *PLoS ONE* **2011**, *6*, e27961. [CrossRef] [PubMed]
72. Purwandari, A.R. Sari DNRSystem of Leukocytes Respiratory Burst Activity (RBA) in Grouper (*Epinephelus coioides*). *J. Biota* **2022**, *8*, 25–32. [CrossRef]
73. Lim, C.; Lee, C.S.; Webster, C.D. (Eds.) *Alternative Protein Sources in Aquaculture Diets*; CRC Press: Boca Raton, FL, USA, 2023.
74. Liu, C.H.; Chiu, C.H.; Wang, S.W.; Cheng, W. Dietary administration of the probiotic, *Bacillus subtilis* E20, enhances the growth, innate immune responses, and disease resistance of the grouper, *Epinephelus coioides*. *Fish Shellfish Immunol.* **2012**, *33*, 699–706. [CrossRef]
75. Abarike, E.D.; Cai, J.; Lu, Y.; Yu, H.; Chen, L.; Jian, J.; Tang, J.; Jun, L.; Kuebutornye, F.K. Effects of a commercial probiotic BS containing *Bacillus subtilis* and *Bacillus licheniformis* on growth, immune response and disease resistance in Nile tilapia, *Oreochromis niloticus*. *Fish Shellfish Immunol.* **2018**, *82*, 229–238. [CrossRef]
76. Du, Y.; Xu, W.; Wu, T.; Li, H.; Hu, X.; Chen, J. Enhancement of growth, survival, immunity and disease resistance in *Litopenaeus vannamei*, by the probiotic, *Lactobacillus plantarum* Ep-M17. *Fish Shellfish Immunol.* **2022**, *129*, 36–51. [CrossRef]
77. Akbari, H.; Shekrabi, S.P.H.; Soltani, M.; Mehrgan, M.S. Effects of potential probiotic *Enterococcus casseliflavus* (EC-001) on growth performance, immunity, and resistance to *Aeromonas hydrophila* infection in common carp (*Cyprinus carpio*). *Probiotics Antimicrob. Proteins* **2021**, *13*, 1316–1325. [CrossRef]
78. Hooshyar, Y.; Abedian Kenari, A.; Paknejad, H.; Gandomi, H. Effects of *Lactobacillus rhamnosus* ATCC 7469 on different parameters related to health status of rainbow trout (*Oncorhynchus mykiss*) and the protection against *Yersinia ruckeri*. *Probiotics Antimicrob. Proteins* **2020**, *12*, 1370–1384. [CrossRef]
79. Tapia-Paniagua, S.T.; Vidal, S.; Lobo, C.; Prieto-Álamo, M.J.; Jurado, J.; Cordero, H.; Cerezuela, R.; Banda, G.; Esteban, M.A.; Balebona, M.C.; et al. The treatment with the probiotic *Shewanella putrefaciens* Pdp11 of specimens of Solea senegalensis exposed to high stocking densities to enhance their resistance to disease. *Fish Shellfish Immunol.* **2014**, *41*, 209–221. [CrossRef]
80. Carbone, D.; Faggio, C. Importance of prebiotics in aquaculture as immunostimulants. Effects on immune system of *Sparus aurata* and *Dicentrarchus labrax*. *Fish Shellfish. Immunol.* **2016**, *54*, 172–178. [CrossRef] [PubMed]
81. Nawaz, A.; Irshad, S.; Hoseinifar, S.H.; Xiong, H. The functionality of prebiotics as immunostimulant: Evidences from trials on terrestrial and aquatic animals. *Fish Shellfish Immunol.* **2018**, *76*, 272–278. [CrossRef]
82. Hoseinifar, S.H.; Sun, Y.Z.; Zhou, Z.; Van Doan, H.; Davies, S.J.; Harikrishnan, R. Boosting immune function and disease bio-control through environment-friendly and sustainable approaches in finfish aquaculture: Herbal therapy scenarios. *Rev. Fish. Sci. Aquac.* **2020**, *28*, 303–321. [CrossRef]
83. Vazirzadeh, A.; Marhamati, A.; Rabiee, R.; Faggio, C. Immunomodulation, antioxidant enhancement and immune genes up-regulation in rainbow trout (*Oncorhynchus mykiss*) fed on seaweeds included diets. *Fish Shellfish Immunol.* **2020**, *106*, 852–858. [CrossRef] [PubMed]
84. Lillehaug, A.; Børnes, C.; Grave, K. A pharmaco-epidemiological study of antibacterial treatments and bacterial diseases in Norwegian aquaculture from 2011 to 2016. *Dis. Aquat. Org.* **2018**, *128*, 117–125. [CrossRef] [PubMed]
85. Savaş, S.; Kubilay, A.; Basmaz, N. Effect of bacterial load in feeds on intestinal microflora of seabream (*Sparus surata*) larvae and juveniles. *Isr. J. Aquac. Bamidgeh* **2005**, *57*, 3–9. [CrossRef]
86. Mussatto, S.I.; Mancilha, I.M. Non-digestible oligosaccharides: A review. *Carbohydr. Polym.* **2007**, *68*, 587–597. [CrossRef]
87. Anjum, J.; Quach, A.; Wongkrasant, P.; Nazir, S.; Tariq, M.; Barrett, K.E.; Zaidi, A. Potentially probiotic *Limosilactobacillus reuteri* from human milk strengthens the gut barrier in T84 cells and a murine enteroid model. *J. Appl. Microbiol.* **2023**, *134*, lxac029. [CrossRef]
88. Hahor, W.; Thongprajukaew, K.; Suanyuk, N. Effects of dietary supplementation of oligosaccharides on growth performance, gut health and immune response of hybrid catfish (*Pangasianodon gigas* × *Pangasianodon hypophthalmus*). *Aquaculture* **2019**, *507*, 97–107. [CrossRef]
89. Lu, Z.Y.; Jiang, W.D.; Wu, P.; Liu, Y.; Kuang, S.Y.; Tang, L.; Yang, J.; Zhou, X.; Feng, L. Mannan oligosaccharides supplementation enhanced head-kidney and spleen immune function in on-growing grass carp (*Ctenopharyngodon idella*). *Fish Shellfish Immunol.* **2020**, *106*, 596–608. [CrossRef]

90. Khosravi-Katuli, K.; Mohammadi, Y.; Ranjbaran, M.; Ghanaatian, H.; Khazaali, A.; Paknejad, H.; Santander, J. Effects of mannan oligosaccharide and synbiotic supplementation on growth performance and immune response of Gilthead Sea Bream (*Sparus aurata*) before and after thermal stress. *Aquac. Res.* **2021**, *52*, 3745–3756. [CrossRef]
91. Lu, J.; Qi, C.; Limbu, S.M.; Han, F.; Yang, L.; Wang, X.; Xin, J.G.; Chen, L. Dietary mannan oligosaccharide (MOS) improves growth performance, antioxidant capacity, non-specific immunity and intestinal histology of juvenile Chinese mitten crabs (*Eriocheir sinensis*). *Aquaculture* **2019**, *510*, 337–346. [CrossRef]
92. Torrecillas, S.; Makol, A.; Caballero, M.J.; Montero, D.; Robaina, L.; Real, F.; Sweetman, J.; Tort, L.; Izquierdo, M.S. Immune stimulation and improved infection resistance in European sea bass (*Dicentrarchus labrax*) fed mannan oligosaccharides. *Fish Shellfish Immunol.* **2007**, *23*, 969–981. [CrossRef]
93. Alak, G.; Atamanalp, M. Usage of probiotics and prebiotics in aquaculture. *Yüzüncü Yil Üniversitesi J. Agric. Sci.* **2012**, *22*, 62–68.
94. Mustafa, A.; Buentello, A.; Gatlin, D., III; Lightner, D.; Hume, M.; Lawrence, A. Effects of fructooligosaccharides (FOS) on growth, survival, gut microflora, stress, and immune response in Pacific white shrimp, *Litopenaeus vannamei*, cultured in a recirculating system. *J. Immunoass. Immunochem.* **2020**, *41*, 45–59. [CrossRef] [PubMed]
95. Li, P.; Wang, X.; Murthy, S.; Gatlin, D.M., III; Castille, F.L.; Lawrence, A.L. Effect of dietary supplementation of brewer's yeast and Grobiotic®-A on growth, immune responses, and low-salinity tolerance of Pacific white shrimp *Litopenaeus vannamei* cultured in recirculating systems. *J. Appl. Aquac.* **2009**, *21*, 110–119. [CrossRef]
96. Gatlin, D.M., III; Li, P.; Wang, X.; Burr, G.S.; Castille, F.; Lawrence, A.L. Potential application of prebiotics in aquaculture. In *Avances en Nutrición Acuicola*; Universidad Autónoma de Nuevo León: Monterrey, Mexico, 2006; ISBN 970-694-333-5.
97. Li, T.; Chu, C.; Zhang, Y.; Ju, M.; Wang, Y. Contrasting eutrophication risks and countermeasures in different water bodies: Assessments to support targeted watershed management. *Int. J. Environ. Res. Public Health* **2017**, *14*, 695. [CrossRef]
98. Amiin, M.K.; Lahay, A.F.; Putriani, R.B.; Reza, M.; Putri, S.M.E.; Sumon, M.A.A.; Jamal, M.T.; Santanumurti, M.B. The role of probiotics in vannamei shrimp aquaculture performance–A review. *Vet. World* **2023**, *16*, 638. [CrossRef]
99. Javahery, S.; Noori, A.; Hoseinifar, S.H. Growth performance, immune response, and digestive enzyme activity in Pacific white shrimp, *Penaeus vannamei* Boone, 1931, fed dietary microbial lysozyme. *Fish Shellfish Immunol.* **2019**, *92*, 528–535. [CrossRef]
100. Preethi, R.; Thanigaivel, S. Analysis and Evaluation of Probiotic (*Lactococcus*) Based Feed Supplements to Improve the Growth and Immune Related Responses of Rohu Fishes. *ECS Trans.* **2022**, *107*, 14051.
101. Eissa, E.S.H.; Ahmed, R.A.; Abd Elghany, N.A.; Elfeky, A.; Saadony, S.; Ahmed, N.H.; Sakr, S.E.; Tolenada, C.P.; Atienza, A.A.; Mabrok, M.; et al. Potential Symbiotic Effects of β-1, 3 Glucan, and Fructooligosaccharides on the Growth Performance, Immune Response, Redox Status, and Resistance of Pacific White Shrimp, *Litopenaeus vannamei* to *Fusarium solani* Infection. *Fishes* **2023**, *8*, 105. [CrossRef]
102. Kolanchinathan, P.; Kumari, P.R.; Raja, K.; John, G.; Balasundaram, A. Analysis of feed composition and growth parameters of *Penaeus monodon* supplemented with two probiotic species and formulated diet. *Aquaculture* **2022**, *549*, 737740. [CrossRef]
103. Wang, Y.; Al Farraj, D.A.; Vijayaraghavan, P.; Hatamleh, A.A.; Biji, G.D.; Rady, A.M. Host associated mixed probiotic bacteria induced digestive enzymes in the gut of tiger shrimp *Penaeus monodon*. *Saudi J. Biol. Sci.* **2020**, *27*, 2479–2484. [CrossRef] [PubMed]
104. Pan, M.V.; Ferriols, V.M.E.N.; Traifalgar, R.F.M. Synergistic influence of hydrolyzed squid processing by-products and Bacillus probiotics as dietary supplements on growth performance, immunological responses, and gut health of juvenile black tiger shrimp fed fishmeal-free diets. *Aquac. Int.* **2024**, *32*, 4551–4580. [CrossRef]
105. NavinChandran, M.; Iyapparaj, P.; Moovendhan, S.; Ramasubburayan, R.; Prakash, S.; Immanuel, G.; Palavesam, A. Influence of probiotic bacterium *Bacillus cereus* isolated from the gut of wild shrimp *Penaeus monodon* in turn as a potent growth promoter and immune enhancer in *P. monodon*. *Fish Shellfish Immunol.* **2014**, *36*, 38–45. [CrossRef] [PubMed]
106. Chandran, M.N.; Suganya, A.M.; Immanuel, G.; Palavesam, A. Immunomodulatory and growth-promoting potential of low-cost probiotic product in *Penaeus monodon* culture system. *Croat. J. Fish.* **2017**, *75*.
107. Pattukumar, V.; Kanmani, P.; Satish Kumar, R.; Yuvaraj, N.; Paari, A.; Arul, V. Enhancement of innate immune system, survival and yield in *Penaeus monodon* reared in ponds using *Streptococcus phocae* PI 80. *Aquac. Nutr.* **2014**, *20*, 505–513. [CrossRef]
108. Duan, Y.; Zhang, J.; Huang, J.; Jiang, S. Effects of dietary Clostridium butyricum on the growth, digestive enzyme activity, antioxidant capacity, and resistance to nitrite stress of *Penaeus monodon*. *Probiotics Antimicrob. Proteins* **2019**, *11*, 938–945. [CrossRef]
109. Sekar, A.; Packyam, M.; Kim, K. Growth enhancement of shrimp and reduction of shrimp infection by *Vibrio parahaemolyticus* and white spot syndrome virus with dietary administration of *Bacillus* sp. Mk22. *Microbiol. Biotechnol. Lett.* **2016**, *44*, 261–267. [CrossRef]
110. Utiswannakul, P.; Sangchai, S.; Rengpipat, S. Enhanced growth of black tiger shrimp *Penaeus monodon* by dietary supplementation with Bacillus (BP11) as a probiotic. *J. Aquac. Res. Dev.* **2011**, *2*, 6. [CrossRef]
111. Amenyogbe, E.; Chen, G.; Wang, Z.; Huang, J.; Huang, B.; Li, H. The exploitation of probiotics, prebiotics and synbiotics in aquaculture: Present study, limitations and future directions.: A review. *Aquac. Int.* **2020**, *28*, 1017–1041. [CrossRef]

112. El-Saadony, M.T.; Swelum, A.A.; Ghanima, M.M.A.; Shukry, M.; Omar, A.A.; Taha, A.E.; Salem, H.M.; El-Tahan, A.M.; El-Terabily, K.A.; Abd El-Hack, M.E. Shrimp production, the most important diseases that threaten it, and the role of probiotics in confronting these diseases: A review. *Res. Vet. Sci.* **2022**, *144*, 126–140. [CrossRef]
113. Muthu, C.M.; Vickram, A.S.; Sowndharya, B.B.; Saravanan, A.; Kamalesh, R.; Dinakarkumar, Y. A comprehensive review on the utilisation of probiotics in aquaculture towards sustainable shrimp farming. *Fish Shellfish Immunol.* **2024**, *147*, 109459. [CrossRef] [PubMed]
114. Tamilselvan, M.; Raja, S. Exploring the role and mechanism of potential probiotics in mitigating the shrimp pathogens. *Saudi J. Biol. Sci.* **2024**, *31*, 103938. [CrossRef] [PubMed]
115. Soltani, M.; Ahmadivand, S.; Ringø, E. Bacillus as Probiotics in Shellfish Culture. In *Bacillus Probiotics for Sustainable Aquaculture*; CRC Press: Boca Raton, FL, USA, 2024; pp. 192–207.
116. Abo-Al-Ela, H.G.; Mahdi, S.; Angthong, P.; Rungrassamee, W. Probiotic modulation of key immune macromolecules in shrimp. *Microb. Pathog.* **2025**, *203*, 107463. [CrossRef] [PubMed]
117. Van Hai, N.; Fotedar, R. A review of probiotics in shrimp aquaculture. *J. Appl. Aquac.* **2010**, *22*, 251–266. [CrossRef]
118. Jamal, M.T.; Abdulrahman, I.A.; Al Harbi, M.; Chithambaran, S. Probiotics as alternative control measures in shrimp aquaculture: A review. *J. Appl. Biol. Biotechnol.* **2019**, *7*, 69–77.
119. Zheng, X.; Duan, Y.; Dong, H.; Zhang, J. The effect of *Lactobacillus plantarum* administration on the intestinal microbiota of whiteleg shrimp *Penaeus vannamei*. *Aquaculture* **2020**, *526*, 735331. [CrossRef]
120. Aruta, K.J.C.; Caipang, C.M.A. Local aquatic microflora as a potential source of probionts in biofloc technology for whiteleg shrimp, *Penaeus vannamei*. *Environ. Exp. Biol.* **2025**, *23*, 1–8. [CrossRef]
121. Trujillo, L.E.; Rivera, L.; Hardy, E.; Llumiquinga, E.M.; Garrido, F.; Chávez, J.A.; Abril, V.H.; País-Chanfrau, J.M. Estrategias Naturales para Mejorar el Crecimiento y la Salud en los Cultivos Masivas de Camarón en Ecuador. *Rev. Bionatura* **2017**, *2*, 318–325. [CrossRef]
122. Noman, M.; Kazmi, S.S.U.H.; Saqib, H.S.A.; Fiaz, U.; Pastorino, P.; Barcelò, D.; Tayyab, M.; Liu, W.; Wang, Z.; Yaseen, Z.M. Harnessing probiotics and prebiotics as eco-friendly solution for cleaner shrimp aquaculture production: A state of the art scientific consensus. *Sci. Total Environ.* **2024**, *915*, 169921. [CrossRef]
123. Kari, Z.A.; Wee, W.; Hamid, N.K.A.; Dawood, M.A.; Zakaria, N.N.A.B.; Wei, L.S. The roles of polysaccharides in tilapia farming: A review. *Aquac. Fish.* **2024**, *9*, 20–27. [CrossRef]
124. Kumar, R.; Dharumadurai, D. Growth and immunomodulatory postbiotic effects in shrimp. In *Postbiotics*; Academic Press: Cambridge, MA, USA, 2025; pp. 565–573.
125. Cheng, A.C.; Chang, H.T.; Lee, T.Y.; Lin, J.S.; Liu, C.H. SYNLAC prime probiotics enhances growth performance, and resistance of white shrimp, *Penaeus vannamei* to *Enterocytozoon hepatopenaei* and *Vibrio alginollyticus*: Insights into immune and metabolic pathway modulations. *Fish Shellfish Immunol.* **2024**, *155*, 110016. [CrossRef] [PubMed]
126. Food and Agricultural Organization of the United Nations and World Health Organization. Health and nutritional properties of probiotics in food including powder milk with live lactic acid bacteria. In *Report of a Joint FAO/WHO Expert Consultation on Evaluation of Health and Nutritional Properties of Probiotics in Food Including Powder Milk with Live Lactic Acid Bacteria*; FAO: Rome, Italy, 2021.
127. Bozkurt, M.; Aysul, N.; Küçükyilmaz, K.; Aypak, S.; Ege, G.; Catli, A.U.; Akşit, H.; Çöven, F.; Seyrek, K.; Çınar, M. Efficacy of in-feed preparations of an anticoccidial, multienzyme, prebiotic, probiotic, and herbal essential oil mixture in healthy and *Eimeria* spp.-infected broilers. *Poult. Sci.* **2014**, *93*, 389–399. [CrossRef]
128. Muhammad, Z.; Ramzan, R.; Zhang, R.; Zhang, M. Resistant starch-based edible coating composites for spray-dried microencapsulation of *Lactobacillus acidophilus*, comparative assessment of thermal protection, in vitro digestion and physicochemical characteristics. *Coatings* **2021**, *11*, 587. [CrossRef]
129. Nikiforov-Nikishin, A.; Nikiforov-Nikishin, D.; Kochetkov, N.; Smorodinskaya, S.; Klimov, V. The influence of probiotics of different microbiological composition on histology of the gastrointestinal tract of juvenile *Oncorhynchus mykiss*. *Microsc. Res. Tech.* **2022**, *85*, 538–547. [CrossRef] [PubMed]
130. Weinrauch, A.M.; Hoogenboom, J.L.; Anderson, W.G. A review of reductionist methods in fish gastrointestinal tract physiology. *Comp. Biochem. Physiol. Part B Biochem. Mol. Biol.* **2021**, *254*, 110571. [CrossRef] [PubMed]
131. Sparagon, W.J.; Gentry, E.C.; Minich, J.J.; Vollbrecht, L.; Laurens, L.M.; Allen, E.E.; Sims, N.A.; Dorrestein, P.C.; Kelly, L.W. Nelson, C.E. Fine scale transitions of the microbiota and metabolome along the gastrointestinal tract of herbivorous fishes. *Anim. Microbiome* **2022**, *4*, 33. [CrossRef]
132. Kanani, H.; Javadian, S.R.; Bahram, S. Evaluation of feed efficiency, growth and biochemical parameters of rainbow trout (*Oncorhynchus mikyss*) juveniles fed with different levels of Alphamune prebiotic. *Sustain. Aquac. Health Manag. J.* **2021**, *7*, 47–55. [CrossRef]

133. Maytorena-Verdugo, C.I.; Peña-Marín, E.S.; Alvarez-Villagómez, C.S.; Pérez-Jiménez, G.M.; Sepúlveda-Quiroz, C.A.; Alvarez-González, C.A. Inclusion of mannan-oligosaccharides in diets for tropical gar atractosteus tropicus larvae: Effects on growth, digestive enzymes, and expression of intestinal barrier genes. *Fishes* **2022**, *7*, 127. [CrossRef]
134. Yousefi, M.; Farsani, M.N.; Ghafarifarsani, H.; Raeeszadeh, M. Dietary Lactobacillus helveticus and Gum Arabic improves growth indices, digestive enzyme activities, intestinal microbiota, innate immunological parameters, antioxidant capacity, and disease resistance in common carp. *Fish Shellfish Immunol.* **2023**, *135*, 108652. [CrossRef]
135. Romero, J.; Ringø, E.; Merrifield, D.L. The gut microbiota of fish. In *Aquaculture Nutrition: Gut Health, Probiotics and Prebiotics*; John Willie and the Suns: Hoboken, NJ, USA, 2014; pp. 75–100.
136. Legrand, T.P.; Wynne, J.W.; Weyrich, L.S.; Oxley, A.P. Investigating both mucosal immunity and microbiota in response to gut enteritis in yellowtail kingfish. *Microorganisms* **2020**, *8*, 1267. [CrossRef] [PubMed]
137. Li, X.; Zhou, S.; Zhang, J.; Zhou, Z.; Xiong, Q. Directional changes in the intestinal bacterial community in black soldier fly (*Hermetia illucens*) larvae. *Animals* **2021**, *11*, 3475. [CrossRef]
138. Tsao, J.C.; Zeltzer, L.K. Complementary and alternative medicine approaches for pediatric pain: A review of the state-of-the-science. *Evid. Based Complement. Altern. Med.* **2005**, *2*, 149–159. [CrossRef]
139. Gupta, V.; Garg, R. Probiotics. *Indian J. Med. Microbiol.* **2009**, *27*, 202–209. [CrossRef]
140. Ogunkalu, O. Effects of feed additives in fish feed for improvement of aquaculture. *Eurasian J. Food Sci. Technol.* **2019**, *3*, 49–57.
141. Cuvin-Aralar, M.L.A.; Ricafort, C.H.; Salvacion, A. *An Overview of Agricultural Follution in the Philippines: The Fisheries Sector*; World Bank: Washington, DC, USA, 2016.
142. Rahman, M.M.; Khosravi, S.; Chang, K.H.; Lee, S.M. Effects of dietary inclusion of astaxanthin on growth, muscle pigmentation and antioxidant capacity of juvenile rainbow trout (*Oncorhynchus mykiss*). *Prev. Nutr. Food Sci.* **2016**, *21*, 281. [CrossRef] [PubMed]
143. Zhao, W.; Guo, Y.C.; Huai, M.Y.; Li, L.; Man, C.; Pelletier, W.; Wei, H.L.; Yao, R.; Niu, J. Comparison of the Retention Rates of Synthetic and Natural Astaxanthin in Feeds and Their Effects on Pigmentation, Growth, and Health in Rainbow Trout (*Oncorhynchus mykiss*). *Antioxidants* **2022**, *11*, 2473. [CrossRef]
144. Song, X.; Wang, L.; Li, X.; Chen, Z.; Liang, G.; Leng, X. Dietary astaxanthin improved the body pigmentation and antioxidant function, but not the growth of discus fish (*Symphysodon* spp.). *Aquac. Res.* **2017**, *48*, 1359–1367. [CrossRef]
145. Lall, S.P.; Kaushik, S.J. Nutrition and metabolism of minerals in fish. *Animals* **2021**, *11*, 2711. [CrossRef]
146. Liu, Z.L.; Zhao, W.; Hu, W.S.; Zhu, B.; Xie, J.J.; Liu, Y.J.; Tian, L.X.; Niu, J. Lipid metabolism, growth performance, antioxidant ability and intestinal morphology of rainbow trout (*Oncorhynchus mykiss*) under cage culture with flowing water were affected by dietary lipid levels. *Aquac. Rep.* **2021**, *19*, 100593. [CrossRef]
147. Wen, B.; Jiang, Y.; Yuan, R.; Heqiu, Y.; Liu, Q.; Li, X.; Zuo, R. Effects of dietary lipid sources on the survival, growth, body composition, antioxidant capacity and expression of antioxidant and pro-inflammatory genes in juvenile Chinese mitten crab (*Eriocheir sinensis*) reared under three salinities. *Aquac. Res.* **2021**, *52*, 5307–5320. [CrossRef]
148. Ibrahim, S.A.; Ayivi, R.D.; Zimmerman, T.; Siddiqui, S.A.; Altemimi, A.B.; Fidan, H.; Esatbeyoglu, T.; Bakhshayesh, R.V. Lactic acid bacteria as antimicrobial agents: Food safety and microbial food spoilage prevention. *Foods* **2021**, *10*, 3131. [CrossRef]
149. Nasrollahzadeh, A.; Mokhtari, S.; Khomeiri, M.; Saris, P. EAntifungal preservation of food by lactic acid bacteria. *Foods* **2022**, *11*, 395. [CrossRef] [PubMed]
150. Luo, Z.Z.; Sun, H.M.; Guo, J.W.; Luo, P.; Hu, C.Q.; Huang, W.; Shu, H. Molecular characterisation of a RNA polymerase (RNAP) II (DNA directed) polypeptide H (POLR2H) in Pacific white shrimp (*Litopenaeus vannamei*) and its role in response to high-pH stress. *Fish Shellfish Immunol.* **2020**, *96*, 245–253. [CrossRef]
151. Korkmaz, K. The Effect of Sodium Bicarbonate Injection on the Physico-Chemical Quality of Post-Harvest Trout. *Foods* **2023**, *12*, 2437. [CrossRef]
152. Li, X.; Zheng, S.; Wu, G. Nutrition and metabolism of glutamate and glutamine in fish. *Amino Acids* **2020**, *52*, 671–691. [CrossRef] [PubMed]
153. Rachmawati, D.; Nurhayati, D. Effect of dietary lysine on the growth performance of Pangasius hypophthalmus. *Depik* **2022**, *11*, 111–116. [CrossRef]
154. Guo, J.; Duan, M.; Qiu, X.; Masagounder, K.; Davis, D.A. Characterisation of methionine uptake and clearance in the hemolymph of Pacific white shrimp *Litopenaeus vannamei*. *Aquaculture* **2020**, *526*, 735351. [CrossRef]
155. Ahmmed, M.K.; Ahmmed, F.; Tian, H.; Carne, A.; Bekhit, A.E.D. Marine omega-3 (n-3) phospholipids: A comprehensive review of their properties, sources, bioavailability, and relation to brain health. *Compr. Rev. Food Sci. Food Saf.* **2020**, *19*, 64–123. [CrossRef]
156. Aragão, C.; Teodósio, R.; Colen, R.; Richard, N.; Rønnestad, I.; Dias, J.; Conceição, L.E.C.; Ribeiro, L. Taurine Supplementation to Plant-Based Diets Improves Lipid Metabolism in Senegalese Sole. *Animals* **2023**, *13*, 1501. [CrossRef]
157. Koven, W.; Bracha, C.; Nixon, O.; Israeli, D.; Tandler, A.; Meiri-Ashkenazi, I.; Rosenfeld, H. The effect of dietary taurine and its potential biosynthesis on juvenile grey mullet (*Mugil cephalus*) performance. *Isr. J. Aquac. Bamidgeh* **2023**, *75*, 1–15. [CrossRef]

158. Chen, S.; Yu, Y.; Gao, Y.; Yin, P.; Tian, L.; Niu, J.; Liu, Y. Exposure to acute ammonia stress influences survival, immune response and antioxidant status of pacific white shrimp (*Litopenaeus vannamei*) pretreated with diverse levels of inositol. *Fish Shellfish Immunol.* **2019**, *89*, 248–256. [CrossRef]
159. Kong, F.; Zhu, Y.; Yu, H.; Wang, X.; Azm, F.R.A.; Yuan, J.; Tan, Q. Effect of dietary vitamin C on the growth performance, non-specific immunity and antioxidant ability of red swamp crayfish (*Procambarus clarkii*). *Aquaculture* **2021**, *541*, 736785. [CrossRef]
160. Sreekanth, G.B.; Varghese, T.; Mishal, P.; Sandeep, K.P.; Praveen, K.V. Food security in India: Is aquaculture a solution in the offing. *Int. J. Sci. Res.* **2015**, *4*, 553–560.
161. Gaponov, N.V.; Gamko, L.N. Nutrient digestibility of fishmeal rations in primates. *Vet. Sci. Today* **2021**, *10*, 239–242. [CrossRef]
162. Souza, C.D.F.; Baldissera, M.D.; Baldisserotto, B.; Heinzmann, B.M.; Martos-Sitcha, J.A.; Mancera, J.M. Essential oils as stress-reducing agents for fish aquaculture: A review. *Front. Physiol.* **2019**, *10*, 785. [CrossRef] [PubMed]
163. Zheng, X.; Bossier, P. Toxicity assessment and anti-Vibrio activity of essential oils: Potential for application in shrimp aquaculture. *Rev. Aquac.* **2023**, *15*, 1554–1573. [CrossRef]
164. Mbokane, E.M.; Moyo, N.A.G. Use of medicinal plants as feed additives in the diets of Mozambique tilapia (*Oreochromis mossambicus*) and the African Sharptooth catfish (*Clarias gariepinus*) in Southern Africa. *Front. Vet. Sci.* **2022**, *9*, 1072369. [CrossRef]
165. Yousefian, M.; Amiri, M.S. A review of the use of prebiotic in aquaculture for fish and shrimp. *Afr. J. Biotechnol.* **2009**, *8*, 7313–7318.
166. Sitjà-Bobadilla, A. Nutritional Interventions to Mitigate Parasitic Enteritis. *Aquac. Eur.* 2017, 17. Available online: http://hdl.handle.net/10261/191297 (accessed on 7 May 2025).
167. Muthulakshmi, M.; Subramani, P.A.; Michael, R.D. Immunostimulatory effect of the aqueous leaf extract of Phyllanthus niruri on the specific and non-specific immune responses of *Oreochromis mossambicus* Peters. *Iran. J. Vet. Res.* **2016**, *17*, 200. [PubMed]
168. Salem, M.O.A.; Taştan, Y.; Bilen, S.; Terzi, E.; Sönmez, A.Y. Effects of white mustard (*Sinapis alba*) oil on growth performance, immune response, blood parameters, digestive and antioxidant enzyme activities in rainbow trout (*Oncorhynchus mykiss*). *Fish Shellfish Immunol.* **2022**, *131*, 283–299. [CrossRef]
169. Immanuel, G.; Uma, R.P.; Iyapparaj, P.; Citarasu, T.; Punitha Peter, S.M.; Michael Babu, M.; Palavesam, A. Dietary medicinal plant extracts improve growth, immune activity and survival of tilapia *Oreochromis mossambicus*. *J. Fish Biol.* **2009**, *74*, 1462–1475. [CrossRef]
170. Jahanjoo, V.; Yahyavi, M.; Akrami, R.; Bahri, A.H. Influence of adding garlic (*Allium sativum*), Ginger (*Zingiber officinale*), thyme (*Thymus vulgaris*) and their combination on the growth performance, haematoimmunological parameters and disease resistance to Photobacterium damselae in sobaity sea bream (*Sparidentex hasta*) Fry. *Turk. J. Fish. Aquat. Sci.* **2024**, *18*, 633–645.
171. Alam, S.; Afzal, G.; Siddique, A.B.; Afzal, M.; Shahid, M.; Ramzan, A.; Iqbal, Z.; Ali, H.M.; Hira Ahsan, H.; Khan, M.S.; et al. Essential Oil-Based Functional Feeds for Promoting Growth in Aquaculture Species. *Complement. Altern. Med. Essent. Oils* **2024**, 199–206. [CrossRef]
172. Dawood, M.A.; El Basuini, M.F.; Yilmaz, S.; Abdel-Latif, H.M.; Alagawany, M.; Kari, Z.A.; Razab, M.K.; Hamid, N.K.; Moonmanee, T.; Van Doan, H. Exploring the roles of dietary herbal essential oils in aquaculture: A review. *Animals* **2022**, *12*, 823. [CrossRef]
173. Awad, E.; Awaad, A. Role of medicinal plants on growth performance and immune status in fish. *Fish Shellfish Immunol.* **2017**, *67*, 40–54. [CrossRef]
174. Ahmadifar, E.; Yousefi, M.; Karimi, M.; Fadaei Raieni, R.; Dadar, M.; Yilmaz, S.; Dawood, M.A.O.; Abdel-Latif, H.M. Benefits of dietary polyphenols and polyphenol-rich additives to aquatic animal health: An overview. *Rev. Fish. Sci. Aquac.* **2021**, *29*, 478–511. [CrossRef]
175. Ashry, A.M.; Habiba, M.M.; El-Zayat, A.M.; Hassan, A.M.; Moonmanee, T.; Van Doan, H.; Shadrack, R.S.; Dawood, M.A. Dietary anise (*Pimpinella anisum* L.) enhances growth performance and serum immunity of European sea bass (*Dicentrarchus labrax*). *Aquac. Rep.* **2022**, *23*, 101083. [CrossRef]
176. Ashry, A.M.; Habiba, M.M.; Abdel-Wahab, A.; Younis, E.M.; Davies, S.J.; Elnakeeb, M.A.; Abdelghany, M.F.; El-Zayat, A.M.; El-Sebaey, A.M. Dietary effect of powdered herbal seeds on zootechnical performance, hemato-biochemical indices, immunological status, and intestinal microbiota of European sea bass (*Dicentrarchus labrax*). *Aquac. Rep.* **2024**, *36*, 102074. [CrossRef]
177. Kalaiselvan, P.; Malarvizhi, K.; Ranjan, A. Exploring phytobiotics in aquaculture: Sources, mode of action, effects, administration, and its bioavailability in fish. *Aquac. Int.* **2024**, *32*, 5737–5799. [CrossRef]
178. Chakraborty, S.B.; Hancz, C. Application of phytochemicals as immunostimulant, antipathogenic and antistress agents in finfish culture. *Rev. Aquac.* **2011**, *3*, 103–119. [CrossRef]
179. Olaniyi, C.O.; Atoyebi, M.O.; Obafunmiso, H.T.; Salaam, K.A. Effect of ginger (*Zingiber officinale*) in the nutrition of African catfish-A cholesterol reducer and fertility enhancer. *Int. J. Aquac. Fish. Sci.* **2020**, *6*, 21–28. [CrossRef]
180. Oparaku, N.F.; Ijem, N.; Nduka, J.C. Growth performance of Clarias gariepinus (*African catfish*) juveniles fed Zingiber officinale (*Ginger*) and Moringa oleifera bark supplemented diets. *Acad. J. Med. Plants* **2021**, *9*, 147–153.

181. Wei, L.S.; Kari, Z.A.; Kabir, M.A.; Khoo, M.I.; Azra, M.N.; Wee, W. Promoting growth and health of African catfish, Clarias gariepinus, through dietary novel supplement, ginger, zingiber officinale rosc, leaf powder. *Aquac. Stud.* **2023**, *24*, AQUAST1719. [CrossRef]
182. Wijayanto, D. The effect of ginger (*Zingiber officinale*) enrichment in artificial feed on the growth, survival, and profitability of giant gourami (*Osphronemus goramy*) cultivation. *Aquac. Aquar. Conserv. Legis.* **2025**, *18*, 269–276.
183. Gabriel, N.N.; Wilhelm, M.R.; Habte-Tsion, H.M.; Chimwamurombe, P.; Omoregie, E.; Iipinge, L.N.; Shimooshili, K. Effect of dietary Aloe vera polysaccharides supplementation on growth performance, feed utilisation, hemato-biochemical parameters, and survival at low pH in African catfish (*Clarias gariepinus*) fingerlings. *Int. Aquat. Res.* **2019**, *11*, 57–72. [CrossRef]
184. Jaafar, N.; Musa, S.M.; Azfaralariff, A.; Mohamed, M.; Yusoff, A.H.; Lazim, A.M. Improving the efficiency of post-digestion method in extracting microplastics from gastrointestinal tract and gills of fish. *Chemosphere* **2020**, *260*, 127649. [CrossRef]
185. Tartila, S.S.Q.; Jusadi, D.; Setiawati, M.; Fauzi, I.A. Evaluation of dietary supplementation with cinnamon products on growth, blood composition, liver structure, and meat quality of striped catfish (*Pangasianodon hypophthalmus*). *Aquac. Int.* **2021**, *29*, 2243–2257. [CrossRef]
186. Mahboub, H.H.; Tartor, Y.H. Carvacrol essential oil stimulates growth performance, immune response, and tolerance of Nile tilapia to Cryptococcus uniguttulatus infection. *Dis. Aquat. Org.* **2020**, *141*, 1–14. [CrossRef]
187. Kazempoor, R.; Alavinezhad, S.S.; Pargari, M.M.; Shakeri, Y.S.; Haghighi, M.M. A review on the application of phytogenics as feed additives for aquatic animals. *Int. J. Aquat. Res. Environ. Stud.* **2022**, *2*, 46–78. [CrossRef]
188. Onomu, A.J.; Okuthe, G.E. The role of functional feed additives in enhancing aquaculture sustainability. *Fishes* **2024**, *9*, 167. [CrossRef]
189. Tignani, M.V.; Santolini, E.; Secci, G.; Bovo, M.; Parisi, G.; Barbaresi, A. Assessing environmental sustainability of substitute feeding formulas for gilthead seabream (*Sparus aurata*) using Life Cycle Assessment. *Sci. Total Environ.* **2024**, *954*, 176689. [CrossRef]
190. Doyle, M.P.; Erickson, M.C. Opportunities for mitigating pathogen contamination during on-farm food production. *Int. J. Food Microbiol.* **2012**, *152*, 54–74. [CrossRef] [PubMed]
191. Puvanasundram, P.; Chong, C.M.; Sabri, S.; Yusoff, M.S.; Karim, M. Multi-strain probiotics: Functions, effectiveness and formulations for aquaculture applications. *Aquac. Rep.* **2021**, *21*, 100905. [CrossRef]
192. Dima, M.F.; Sîrbu, E.; Patriche, N.; Cristea, V.; Coadă, M.T.; Plăcintă, S. Effects of multi-strain probiotics on the growth and hematological profile in juvenile carp (*Cyprinus carpio*, Linnaeus 1758). *Carpathian J. Food Sci. Technol.* **2022**, *14*, 5–20. [CrossRef]
193. Kuebutornye, F.K.; Abarike, E.D.; Lu, Y.; Hlordzi, V.; Sakyi, M.E.; Afriyie, G.; Wang, Z.; Li, Y.; Xie, C.X. Mechanisms and the role of probiotic Bacillus in mitigating fish pathogens in aquaculture. *Fish Physiol. Biochem.* **2020**, *46*, 819–841. [CrossRef]
194. Midhun, S.J.; Arun, D.; Jyothis, M. Probiotic application of beneficial bacteria for improved health and disease control. In *Recent Advances in Aquaculture Microbial Technology*; Academic Press: Cambridge, MA, USA, 2023; pp. 275–289.
195. Calcagnile, M.; Tredici, S.M.; Alifano, P. A comprehensive review on probiotics and their use in aquaculture: Biological control, efficacy, and safety through the genomics and wet methods. *Heliyon* **2024**, *10*, e40892. [CrossRef]
196. Moon, K.; Ryu, S.; Song, S.H.; Chun, S.W.; Lee, N.; Lee, A.H. Characterization of novel bacteriophages for effective phage therapy against Vibrio infections in aquaculture. *J. Microbiol.* **2025**, *63*, e2502009. [CrossRef]
197. Hashem, N.M.; Hosny, N.S.; El-Desoky, N.; Soltan, Y.A.; Elolimy, A.A.; Sallam, S.M.; Abu-Tor, E.S.M. Alginate nanoencapsulated synbiotic composite of pomegranate peel phytogenics and multi-probiotic species as a potential feed additive: Physicochemical, antioxidant, and antimicrobial activities. *Animals* **2023**, *13*, 2432. [CrossRef] [PubMed]
198. MA, A.; Sarasan, M.; Kachiprath, B.; Sukumaran, V.; Singh, I.B.; Puthumana, J. Engineering the fish gut microbiome: Could it serve as future-proof strategy for sustainable aquaculture? *Blue Biotechnol.* **2025**, *2*, 6. [CrossRef]
199. Liu, C.; Ma, N.; Feng, Y.; Zhou, M.; Li, H.; Zhang, X.; Ma, X. From probiotics to postbiotics: Concepts and applications. *Anim. Res. One Health* **2023**, *1*, 92–114. [CrossRef]
200. Dawood, M.A.; Abo-Al-Ela, H.G.; Hasan, M.T. Modulation of transcriptomic profile in aquatic animals: Probiotics, prebiotics and synbiotics scenarios. *Fish Shellfish Immunol.* **2020**, *97*, 268–282. [CrossRef] [PubMed]
201. Quintanilla-Pineda, M.; Achou, C.G.; Díaz, J.; Gutiérrez-Falcon, A.; Bravo, M.; Herrera-Muñoz, J.I.; Peña-Navarro, N.; Alvarado, C.; Ibañez, F.C.; Marzo, F. In vitro evaluation of postbiotics produced from bacterial isolates obtained from rainbow trout and Nile tilapia against the pathogens *Yersinia ruckeri* and *Aeromonas salmonicida* subsp. *salmonicida*. *Foods* **2023**, *12*, 861. [CrossRef]
202. Tao, L.T.; Lu, H.; Xiong, J.; Zhang, L.; Sun, W.W.; Shan, X.F. The application and potential of postbiotics as sustainable feed additives in aquaculture. *Aquaculture* **2024**, *592*, 741237. [CrossRef]
203. Gervasoni, L.F.; Gervasoni, K.; de Oliveira Silva, K.; Mendes, M.E.F.; Maddela, N.R.; Prasad, R.; Winkelstroter, L.K. Postbiotics in active food packaging: The contribution of cellulose nanocomposites. *Sustain. Chem. Pharm.* **2023**, *36*, 101280. [CrossRef]
204. Rovelli, R.; Cecchini, B.; Zavagna, L.; Azimi, B.; Ricci, C.; Esin, S.; Milazzo, M.; Batoni, G.; Danti, S. Emerging Multiscale Biofabrication Approaches for Bacteriotherapy. *Molecules* **2024**, *29*, 533. [CrossRef]

205. Zhang, C.L.; Chen, G.; Ji, X.S.; Teng, J.; Yao, Z.L.; Hu, C.L.; Zhao, Y. Construction and evaluation of recombinant *Lactobacillus plantarum* expressing *Micropterus salmoides* hepcidin. *Microb. Cell Factories* **2025**, *24*, 148. [CrossRef]
206. Jiao, S.; Fu, Y.Z.; Zhang, N.F. Progress on mechanism and functional characteristics of next generation probiotics. *Chin. J. Anim. Nutr.* **2022**, *34*, 4836–4846.
207. Loo, K.Y.; Thong, J.Y.H.; Tan, L.T.H.; Letchumanan, V.; Chan, K.G.; Lee, L.H.; Law, J.W.F. A Current Overview of Next-Generation Probiotics and Their Prospects in Health and Disease Management. *Prog. Microbes Mol. Biol.* **2024**, *7*, 7. [CrossRef]
208. Barbosa, J.C.; Machado, D.; Almeida, D.; Andrade, J.C.; Brandelli, A.; Gomes, A.M.; Freitas, A.C. Next-generation probiotics. In *Probiotics*; Academic Press: Cambridge, MA, USA, 2022; pp. 483–502.
209. Amphan, S.; Unajak, S.; Printrakoon, C.; Areechon, N. Feeding-regimen of β-glucan to enhance innate immunity and disease resistance of Nile tilapia, Oreochromis niloticus Linn., against Aeromonas hydrophila and Flavobacterium columnare. *Fish Shellfish Immunol.* **2019**, *87*, 120–128. [CrossRef]
210. Schmitt, P.; Wacyk, J.; Morales-Lange, B.; Rojas, V.; Guzmán, F.; Dixon, B.; Mercado, L. Immunomodulatory effect of cathelicidins in response to a β-glucan in intestinal epithelial cells from rainbow trout. *Dev. Comp. Immunol.* **2015**, *51*, 160–169. [CrossRef] [PubMed]
211. Wen, C.; Gan, N.; Zeng, T.; Zhang, N.; Zhou, H.; Zhang, A.; Wang, X. Regulation of Il-10 gene expression by Il-6 via Stat3 in grass carp head kidney leucocytes. *Gene* **2020**, *741*, 144579. [CrossRef]
212. Zhou, N.; Chen, L.L.; Chen, J.; Guo, Z.P. Molecular characterization and expression analysis of IL-1β and two types of IL-1 receptor in barbel steed (*Hemibarbus labeo*). *Comp. Biochem. Physiol. Part B Biochem. Mol. Biol.* **2020**, *241*, 110393. [CrossRef] [PubMed]
213. Meng, Y.; Ma, R.; Ma, J.; Han, D.; Xu, W.; Zhang, W.; Mai, K. Dietary nucleotides improve the growth performance, antioxidative capacity and intestinal morphology of turbot (*Scophthalmus maximus*). *Aquac. Nutr.* **2017**, *23*, 585–593. [CrossRef]
214. Magouz, F.I.; Abdel-Rahim, M.M.; Lotfy, A.M.; Mosbah, A.; Alkafafy, M.; Sewilam, H.; Dawood, M.A. Dietary nucleotides enhanced growth performance, carcass composition, blood biochemical, and histology features of European sea bass, *Dicentrarchus labrax* L. *Aquac. Rep.* **2021**, *20*, 100738.
215. Taklu, M.; Islami, H.R.; Mousavi, S.A.; Jourdehi, A.Y. Nucleotide supplementation in the diet of Sterlet sturgeon (*Acipenser ruthenus*): Improved zootechnical performance, biochemical indices, and immune responses. *Anim. Feed Sci. Technol.* **2022**, *288*, 115322. [CrossRef]
216. Doo, E.H.; Chassard, C.; Schwab, C.; Lacroix, C. Effect of dietary nucleosides and yeast extracts on composition and metabolic activity of infant gut microbiota in PolyFermS colonic fermentation models. *FEMS Microbiol. Ecol.* **2017**, *93*, fix088. [CrossRef]
217. Zhou, W.; Ramachandran, D.; Mansouri, A.; Dailey, M.J. Glucose stimulates intestinal epithelial crypt proliferation by modulating cellular energy metabolism. *J. Cell. Physiol.* **2018**, *233*, 3465–3475. [CrossRef]
218. Ringø, E.; Van Doan, H.; Lee, S.H.; Soltani, M.; Hoseinifar, S.H.; Harikrishnan, R.; Song, S.K. Probiotics, lactic acid bacteria and bacilli: Interesting supplementation for aquaculture. *J. Appl. Microbiol.* **2020**, *129*, 116–136. [CrossRef]
219. Madhulika Ngasotter, S.; Meitei, M.M.; Kara, T.; Meinam, M.; Sharma, S.; Rathod, S.K.; Singh, S.B.; Singh, S.K.; Bhat, R.A.H. Multifaceted Role of Probiotics in Enhancing Health and Growth of Aquatic Animals: Mechanisms, Benefits, and Applications in Sustainable Aquaculture—A Review and Bibliometric Analysis. *Aquac. Nutr.* **2025**, *1*, 5746972. [CrossRef] [PubMed]
220. Corr, S.C.; Hill, C.; Gahan, C.G. Understanding the mechanisms by which probiotics inhibit gastrointestinal pathogens. *Adv. Food Nutr. Res.* **2009**, *56*, 1–15.
221. Aleman, R.S.; Yadav, A. Systematic review of probiotics and their potential for developing functional nondairy foods. *Appl. Microbiol.* **2023**, *4*, 47–69. [CrossRef]
222. Alsufyani, M.O.; Asiri, A.A.; Asiri, Y.M.; Alsughayyir, I.A.; Alzahrani, R.A.; Al Essa, T.A.; Lajhar, A.M.; Alshhrani, M.A.; Rabeh, M.A. Correlation between Probiotic and Prebiotic: A Systematic review. *Egypt. J. Chem.* **2024**, *67*, 2227–2244. [CrossRef]
223. Yoo, S.; Jung, S.C.; Kwak, K.; Kim, J.S. The role of prebiotics in modulating gut microbiota: Implications for human health. *Int. J. Mol. Sci.* **2024**, *25*, 4834. [CrossRef] [PubMed]
224. Kumari, T.; Bag, K.K.; Das, A.B.; Deka, S.C. Synergistic role of prebiotics and probiotics in gut microbiome health: Mechanisms and clinical applications. *Food Bioeng.* **2024**, *3*, 407–424. [CrossRef]
225. Caipang, C.M.A.; Suharman, I.; Avillanosa, A.L.; Gonzales-Plasus, M.M. Influence of phytogenic feed additives on the health status in the gut and disease resistance of cultured fish. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2021; Volume 695, p. 012024.
226. Firmino, J.P.; Galindo-Villegas, J.; Reyes-López, F.E.; Gisbert, E. Phytogenic bioactive compounds shape fish mucosal immunity. *Front. Immunol.* **2021**, *12*, 695973. [CrossRef]
227. Abdel-Latif, M.A.; Alsenosy, A.A.; Manaa, E.A.; Abaza, S.; Elshenawi, M.A.; Aboelnour, A.; Alagawany, M. Phytobiotics and their application in poultry and aquaculture industry. In *Organic Feed Additives for Livestock*; Academic Press: Cambridge, MA, USA, 2025; pp. 1–16.

228. Dawood, M.A.; El Basuini, M.F.; Zaineldin, A.I.; Yilmaz, S.; Hasan, M.T.; Ahmadifar, E.; El Asely, A.M.; Abdel-Latif, H.M.R.; Alagawany, M.; Abu-Elala, N.M.; et al. Antiparasitic and antibacterial functionality of essential oils: An alternative approach for sustainable aquaculture. *Pathogens* **2021**, *10*, 185. [CrossRef]
229. Ibrahim, D.; Shahin, S.E.; Alqahtani, L.S.; Hassan, Z.; Althobaiti, F.; Albogami, S.; Soliman, M.M.; El-Malt, R.M.S.; Al-Harthi, H.F.; Alqadri, N.; et al. Exploring the interactive effects of thymol and thymoquinone: Moving towards an enhanced performance, gross margin, immunity and Aeromonas sobria resistance of Nile Tilapia (*Oreochromis niloticus*). *Animals* **2022**, *12*, 3034. [CrossRef] [PubMed]
230. Sepehrfar, D.; Sudagar, M.; Paknejad, H.; Yousefi Siahkalroodi, S.; Norouzitallab, P. Role of phytochemicals in farmed fish reproductive performance: A review. *Iran. J. Fish. Sci.* **2023**, *22*, 1039–1068.
231. Zheng, C.C.; Wu, J.W.; Jin, Z.H.; Ye, Z.F.; Yang, S.; Sun, Y.Q.; Fei, H. Exogenous enzymes as functional additives in finfish aquaculture. *Aquac. Nutr.* **2020**, *26*, 213–224. [CrossRef]
232. Gopalraaj, J.; Velayudhannair, K.; Arockiasamy, J.P.; Radhakrishnan, D.K. The effect of dietary supplementation of proteases on growth, digestive enzymes, oxidative stress, and intestinal morphology in fishes–A review. *Aquac. Int.* **2024**, *32*, 745–765. [CrossRef]
233. Ng, W.K.; Koh, C.B. The utilisation and mode of action of organic acids in the feeds of cultured aquatic animals. *Rev. Aquac.* **2017**, *9*, 342–368. [CrossRef]
234. Sardar, P.; Shamna, N.; Sahu, N.P. Acidifiers in aquafeed as an alternate growth promoter: A short review. *Anim. Nutr. Feed Technol.* **2020**, *20*, 353–366. [CrossRef]
235. Flecker, A.S.; Shi, Q.; Almeida, R.M.; Angarita, H.; Gomes-Selman, J.M.; García-Villacorta, R.; Sethi, S.A.; Thomas, S.A.; Poff, N.L.; Forsberg, B.R.; et al. Reducing adverse impacts of Amazon hydropower expansion. *Science* **2022**, *375*, 753–760. [CrossRef] [PubMed]
236. Zhang, T.; Ding, Y.; Peng, J.; Dai, Y.; Luo, S.; Liu, W.; Ma, Y. Effects of broad-spectrum antibiotic (florfenicol) on resistance genes and bacterial community structure of water and sediments in an aquatic microcosm model. *Antibiotics* **2022**, *11*, 1299. [CrossRef]
237. Zhang, T.; Peng, J.; Dai, Y.; Xie, X.; Luo, S.; Ding, Y.; Ma, Y. Effect of florfenicol on nirS-type denitrifying communities structure of water in an aquatic microcosm model. *Front. Vet. Sci.* **2023**, *10*, 1205394. [CrossRef]
238. Khairy, W.M.; El-Ashmawy, N.; Nofal, E.R. Analysing the evolution of environmental impacts due to fish farms expansion. *Int. J. Eng. Tech. Res.* **2020**, *9*, 689–701.
239. Gonzalez Parrao, C.; Shisler, S.; Moratti, M.; Yavuz, C.; Acharya, A.; Eyers, J.; Snilstveit, B. Aquaculture for improving productivity, income, nutrition and women's empowerment in low-and middle-income countries: A systematic review and meta-analysis. *Campbell Syst. Rev.* **2021**, *17*, e1195. [CrossRef] [PubMed]
240. Won, J. Investigating Gasoline Contamination Effects on Daphnia's Heartbeat in a Simulated Lake. *J. Glob. Ecol. Environ.* **2023**, *17*, 20–31. [CrossRef]
241. Reis, J.V.T. The Production Cycle of *Litopenaeus vannamei* in Outdoor Ponds and Tank Culture of *Trachinotus carolinus*. Internship at Auburn University's Fish and Shrimp Nutrition Lab, PQDT-Global. 2017. Source: Repositório Aberto da Universidade do Porto. Available online: https://share.google/NuKzLHbDz0ofNx6CH (accessed on 10 April 2025).
242. Gazi-Khan, L.; Haque, S.E. A review of the current status of water quality and eutrophication in Dhaka's water bodies. *Management* **2022**, *10*, 1–9. [CrossRef]
243. Lenzi, M.; Persiano, M.; Gennaro, P.; Rubegni, F. Wind mitigating action on effects of eutrophication in coastal eutrophic water bodies. *Int. J. Mar. Sci. Ocean Technol.* **2016**, *3*, 14–20. [CrossRef]
244. Hu, Y.; Cheng, H.; Tao, S.; Schnoor, J.L. China's ban on phenylarsonic feed additives, a major step toward reducing the human and ecosystem health risk from arsenic. *Environ. Sci. Technol.* **2019**, *53*, 12177–12187. [CrossRef]
245. El-Seidy, E.; Mohamed, K. General Tit-For-Tat Strategy in The Three Players Prisoner's Dilemma Game. *World Sci. Res.* **2015**, *2*, 1–9.
246. Alayande, K.A.; Aiyegoro, O.A.; Ateba, C.N. Probiotics in animal husbandry: Applicability and associated risk factors. *Sustainability* **2020**, *12*, 1087. [CrossRef]
247. Johnson, M.D.; Dubeux, J.C.; Franzluebbers, A.J. 2 Conducting and Communicating Environmental Impacts of Research: Forage Production, Soil Health, Sustainability. *J. Anim. Sci.* **2022**, *100* (Suppl. S1), 39. [CrossRef]
248. Vutukuru, S.; Bodapati, A.K.; Bhimavarapu, V. Doxycycline induced alterations in the glycogen and protein content of the zebra fish, Danio rerio. *Asian J. Microbiol. Biotechnol. Environ. Sci* **2022**, *1*, 271220031.
249. Zhou, J.; Yun, X.; Wang, J.; Li, Q.; Wang, Y. A review on the ecotoxicological effect of sulphonamides on aquatic organisms. *Toxicol. Rep.* **2022**, *9*, 534–540. [CrossRef]
250. Peng, X.; Zhang, X.; Zhang, S.; Li, Z.; Zhang, H.; Zhang, L.; Wu, Z.; Liu, B. Revealing the response characteristics of periphyton biomass and community structure to sulfamethoxazole exposure in aquaculture water: The perspective of microbial network relationships. *Environ. Pollut.* **2024**, *344*, 123301. [CrossRef]

251. Seoane, M.; Rioboo, C.; Herrero, C.; Cid, Á. Toxicity induced by three antibiotics commonly used in aquaculture on the marine microalga *Tetraselmis suecica* (Kylin) Butch. *Mar. Environ. Res.* **2014**, *101*, 1–7. [CrossRef]
252. Song, C.; Zhang, C.; Fan, L.; Qiu, L.; Wu, W.; Meng, S.; Hu, G.; Kamira, B.; Chen, J. Occurrence of antibiotics and their impacts to primary productivity in fishponds around Tai Lake, China. *Chemosphere* **2016**, *161*, 127–135. [CrossRef]
253. González-Gaya, B.; Cherta, L.; Nozal, L.; Rico, A. An optimised sample treatment method for the determination of antibiotics in seawater, marine sediments and biological samples using LC-TOF/MS. *Sci. Total Environ.* **2018**, *643*, 994–1004. [CrossRef]
254. Chen, H.; Liu, S.; Xu, X.R.; Diao, Z.H.; Sun, K.F.; Hao, Q.W.; Liu, S.S.; Ying, G.G. Tissue distribution, bioaccumulation characteristics and health risk of antibiotics in cultured fish from a typical aquaculture area. *J. Hazard. Mater.* **2018**, *343*, 140–148. [CrossRef]
255. He, L.X.; He, L.Y.; Gao, F.Z.; Wu, D.L.; Ye, P.; Cheng, Y.X.; Chen, Z.Y.; Hu, L.X.; Liu, Y.S.; Chen, J.; et al. Antibiotics, antibiotic resistance genes and microbial community in grouper mariculture. *Sci. Total Environ.* **2022**, *808*, 152042. [CrossRef]
256. Bjelland, H.V.; Føre, M.; Lader, P.; Kristiansen, D.; Holmen, I.M.; Fredheim, A.; Grøtli, E.I.; Fathi, D.E.; Oppedal, F.; Utne, I.B.; et al. Exposed aquaculture in Norway. In Proceedings of the OCEANS 2015-MTS/IEEE Washington, Washington, DC, USA, 19–22 October 2015; pp. 1–10.
257. Saleh, H.M.; Bondouk, I.I.; Salama, E.; Mahmoud, H.H.; Omar, K.; Esawii, H.A. Asphaltene or polyvinylchloride waste blended with cement to produce a sustainable material used in nuclear safety. *Sustainability* **2022**, *14*, 3525. [CrossRef]
258. Gray, W.B.; Shimshack, J.P. The effectiveness of environmental monitoring and enforcement: A review of the empirical evidence. *Rev. Environ. Econ. Policy* **2011**, *5*, 3–24. [CrossRef]
259. Hornsletten, H. Optimisation Model Aimed for the Aquaculture Industry for Fleet Composition and Routing of Wellboats. Master's Thesis, NTNU, Trondheim, Norway, 2017.
260. Codex Alimentarius Commission. Guidelines for the Simple Evaluation of Dietary Exposure to Food Additives (CAC/GL 3-1989) (Originally adopted in 1989, revised in 2014). Food and Agriculture Organization of the United Nations (FAO) and World Health Organization (WHO). Available online: https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%3A%2F%2Fworkspace.fao.org%2Fsites%2Fcodex%2FStandards%2FCXG%2B3-1989%2FCXG_003e.pdf (accessed on 17 October 2024).
261. Forcella, S.; Tantawy, N.; Yilma, J. The development of a four-way linking framework in Egypt: An example of the FAO, OIE and WHO joint activities to facilitate national risk assessment. *Vet. Ital.* **2015**, *51*, 45–50. [PubMed]
262. Mantovani, A.; Aquilina, G.; Cubadda, F.; Marcon, F. Risk-benefit assessment of feed additives in the one health perspective. *Front. Nutr.* **2022**, *9*, 843124. [CrossRef]
263. Munguti, J.; Obiero, K.; Odame, H.; Kirimi, J.; Kyule, D.; Ani, J.; Liti, D. Key limitations of fish feeds, feed management practices, and opportunities in Kenya's aquaculture enterprise. *Afr. J. Food Agric. Nutr. Dev.* **2021**, *21*, 17415–17434. [CrossRef]
264. Cobb, M.L.; Otto, C.M.; Fine, A.H. The animal welfare science of working dogs: Current perspectives on recent advances and future directions. *Front. Vet. Sci.* **2021**, *8*, 666898. [CrossRef]
265. Chesson, A.; Gropp, J.; Mantovani, A.; Roncancio, C. Ten years of EFSA's FEEDAP Panel and its main achievements. *EFSA J.* **2012**, *10*, s1005. [CrossRef]
266. Renshaw, D.W. *Animal Feed Additives. Issues in Toxicology: Regulatory Toxicology in the European Union*; Royal Society of Chemistry: London, UK, 2018.
267. Pauly, T.; Wyss, U. Efficacy testing of silage additives—Methodology and existing schemes. *Grass Forage Sci.* **2019**, *74*, 201–210. [CrossRef]
268. Zhang, X.G. Aquaculture in China. *Species Syst. Sel. Sustain. Aquac.* **2007**, 131–144. [CrossRef]
269. Kumar, P.; Srivastava, A. The Use of Feed and Food Additives in United States. In *Sustainable Use of Feed Additives in Livestock: Novel Ways for Animal Production*; Springer International Publishing: Cham, Switzerland, 2023; pp. 245–281.
270. Upton, H.F.; Cowan, T. *Genetically Engineered Salmon*; US Congressional Research Service: Washington, DC, USA, 2015.
271. Xie, S.; Han, D.; Yang, Y.; Zhang, S. Feed Developments in Freshwater Aquaculture. In *Aquaculture in China: Success Stories and Modern Trends*; John Willie and the Suns: Hoboken, NJ, USA, 2018; pp. 431–450.
272. Winger, R.J. Phosphorus Food Additive Use in the European Union. In *Dietary Phosphorus*; CRC Press: Boca Raton, FL, USA, 2017; pp. 279–312.
273. EFSA Panel on Additives and Products or Substances used in Animal Feed (FEEDAP); Bampidis, V.; Azimonti, G.; Bastos, M.D.L.; Christensen, H.; Durjava, M.; Dusemund, B.; Kouba, M.; López-Alonso, M.; Puente, S.L.; et al. Assessment of the safety of the feed additives acetic acid, calcium acetate and sodium diacetate for fish (FEFANA asbl). *EFSA J.* **2023**, *21*, e08176.
274. Broughton, E.I.; Walker, D.G. Policies and practices for aquaculture food safety in China. *Food Policy* **2010**, *35*, 471–478. [CrossRef]
275. Debeuckelaere, W.; Berbejal, R.P.; Rosell, M.A.G. Food additives, enzymes, and flavourings legislation in the European Union. In *Food Additives and Packaging*; American Chemical Society: Washington, DC, USA, 2014; pp. 41–56.
276. De Angelis, F.; Carreno, I. Achieving sustainability of the EU food chain with feed additives as a key tool: The European Commission intends to modernise the legal framework to foster innovation. *Eur. J. Risk Regul.* **2021**, *12*, 866–870. [CrossRef]

277. Varchenko, O.; Artimonova, I. Formation of organisational and economic mechanism for regulation of agricultural market. *Sci. J. Cahul State Univ. Bogdan Petriceicu Hasdeu Econ. Eng. Stud.* **2018**, *4*, 4–15.
278. Petković, G.; Užar, D. Marketing channels in value creation and delivery of cheese in the Republic of Serbia. *Anal. Ekon. Fak. U Subotici* **2020**, *56*, 101–115. [CrossRef]
279. Rossi, M.A.; Basiri, M.L.; McHenry, J.A.; Kosyk, O.; Otis, J.M.; Van Den Munkhof, H.E.; Bryois, J.; Hübel, C.; Breen, G.; Guo, W.; et al. Obesity remodels activity and transcriptional state of a lateral hypothalamic brake on feeding. *Science* **2019**, *364*, 1271–1274. [CrossRef] [PubMed]
280. Kempf, M.; Reinhard, A.; Beuerle, T. Pyrrolizidine alkaloids (PAs) in honey and pollen-legal regulation of PA levels in food and animal feed required. *Mol. Nutr. Food Res.* **2010**, *54*, 158–168. [CrossRef] [PubMed]
281. Grundmann, O.; Kumar, P.; Rogge, M. ACCPPublic Policy Committee Regulation of dietary supplements nutraceutical products in the United States: An argument for greater oversight uniform standards. *J. Clin. Pharmacol.* **2022**, *62*, 14–16. [CrossRef]
282. Nunes, C.S.; Kunamneni, A.; Kumar, V.; Habte-Tsion, H.M. Registration of food and feed additives (enzymes) in the United States, Canada, and China. In *Enzymes in Human and Animal Nutrition*; Academic Press: Cambridge, MA, USA, 2018; pp. 457–480.
283. Lammersfeld, C.A.; Levin, M.D.; Reilly, P.; Coyne, J.W.; Birdsall, T.C.; Markman, M. Assuring quality of dietary supplements for cancer patients: An integrative formulary systems approach. *Integr. Med. A Clin. J.* **2017**, *16*, 38.