Influences of Feed Additives for Sustainable Aquaculture Production in Asia: A Review

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Abstract

Aquaculture is considered as the primary source to increase fish supply in order to ensure food security and effectively address the nutritional needs of the growing population specially in Asian countries. The utilisation of antibiotics in aquafeeds has been extensively employed in aquaculture of Asian region in order to prevent disease and promote growth. But due to various unfavourable consequences and growing acceptance of the benefits of restricted use of antibiotic administration in aquaculture, the necessity to consider alternate options is urgent. In light of this, the development of eco-friendly feed additives, particularly immunostimulants, for disease control and improved health of aquatic animals is gaining popularity in Asia. The utilisation of natural feed additives has the potential to enhance the efficiency of aquaculture production, reduce the need for medicated treatments, minimise waste discharges, and promote sustainability and long-term profitability. Various high-quality feeds, customised for specific needs, are now supplemented with essential feed additives in the Asian aquaculture industry. The recent focus on functional feed additives has led to the incorporation of probiotics, prebiotics, mycotoxin binders, organic acids, phytogenic compounds, and other medicinal herbs. These feed additives not only boost and support the general health of aquatic animals but also increase consumer confidence in farmed fish. The main objective of the present review is to emphasize the significance of functional feed additives in Asian aquaculture, as they play a vital role in regulating growth, optimising feed utilisation, and enhancing the overall health status of aquatic animals.

Keywords: growth performance, immunity, eco-friendly, sustainable aquaculture

Introduction

Aquaculture is considered as the most rapidly expanding animal-based food-producing business, particularly in Asian countries. Aquatic animal farming is an established part of the national culture, contributing to livelihoods, employment and economic growth, while helping to meet protein, unsaturated fat and micronutrient requirements, improving food security and income generation of the increasing world population (Sultana et al., 2017). Aquaculture production relieves pressure on wild capture fisheries and production is expected to double by 2050 (Lauritzen, 2021). Based on projections provided by the Food and Agriculture Organization (FAO), it is anticipated that the consumption of farm-raised fish and shrimp will constitute approximately 66 % of the global seafood consumption by the year 2030 (FAO, 2022). Sustainable aquaculture is critically important because feeding a huge and growing world population economically cannot be accompanied by environmentally destructive practices (FAO, 2022). The obvious goal is profitable generation of excellent nutrition without exosystemic disruption.

Feed additives are a tool for sustainable aquaculture activities that can be used to make aquaculture production more effective and more efficient. There is a growing international market for fish feed additives, which are essential to the development of a sustainable aquaculture industry. Aquaculture has widely adopted the practice of using antibiotics and other chemicals as a precaution in order to achieve these goals (Wongsasak et al., 2015). Antibiotics are commonly employed in aquaculture for the dual purpose of mitigating or managing bacterial pathogen-induced infectious diseases and promoting growth stimulation (Serrano, 2005).

However, the use of antibiotics has a number of negative consequences, including the emergence of dangerous, antibiotic-resistant pathogens; as a result, the administration of antibiotics in aquaculture is rigorously restricted or prohibited. Public awareness of the excessive use of antibiotics in aquafeeds has led to concerns about the exposure of consumers to AB-resistant bacterial species, leading to their sharply restricted use in aquaculture (Dawood et al., 2018). This raises the need to investigate and develop non-antibiotic growth promoters and means of treating microbial pathogen exposure among aquatic organisms (Carbone and Faggio, 2016).

A prime candidate for the replacement of widespread antibiotic dependence is the application of feed additives with immunostimulatory and other properties that increase disease resistance in aquatic animals. Parameters under consideration in the application of new feed additives are improvements in feed quality, enhancement of growth, improved palatability and increased feeding effectiveness, and decreased feed conversion ratio (FCR). Antioxidants, immunostimulants, and probiotics are among the most common non-nutritive feed additives that are given to feeds or to culture systems in order to achieve desired performance and water quality impacts. Feed manufacturers perceive functional feed additives as a viable strategy to mitigate expenses and diminish the reliance on chemotherapeutics and antibiotics within the aquaculture industry, notwithstanding the fact that this approach leads to an escalation in production costs.

Efficient functional feed additives promote development and immunological response, hence improving fish health and productivity in comparison to feeding them a standard diet. Probiotics, prebiotics, organic acids, phytogenic chemicals, immunological - stimulants, yeast products, and enzymes are all examples of functional feed additives (Alemayehu et al., 2018).

This review revealed that the use of a range of eco-friendly feed additives has resulted in beneficiary impacts in the aquaculture sector. Furthermore, the objective of this review is to examine the scientific literature pertaining to feasible alternatives to the utilisation of antibiotics, thereby making a valuable contribution to the long-term viability of aquaculture practices and ensuring the safety of food products.

Materials and Methods

This review focuses specifically on exploring the influences of feed additives for sustainable aquaculture production in Asian territories. A systematic search of scholarly literature was conducted using the Scopus and Web of Science (WOS) databases, targeting publications available in English and encompassing the title, abstract, and keywords fields (TITLE-ABS-KEY). The primary search term employed was "Feed Additives," combined with various keywords, including "growth performance", "immunity", "eco-friendly", and "sustainable aquaculture".

Following the retrieval of results from the Scopus and Web of Science databases, duplicate papers were initially eliminated. Subsequently, a preliminary screening process was conducted based on a careful examination of titles and abstracts, with articles deemed irrelevant to the specified topics of interest being excluded. The exclusion criteria employed were as follows: a) Studies focusing on non-Asian countries were excluded, b) Articles solely addressing feed additives not related to aquaculture were omitted, and c) Only studies concerning scientifically evaluated or industrially practiced feed additives in aquaculture within Asian countries were considered.

Around 100 selected articles were utilised to compile summary tables, maps, and figures elucidating findings related to the influences of feed additives on sustainable aquaculture production in Asian territories, along with associated challenges and recommendations pertaining to prospects in the region.

Present Scenario of Asian Countries in Global Aquaculture

Asian countries play a crucial and leading role in the global aquaculture production (Garlock et al., 2020). With their abundant coastlines, rivers, and lakes, as well as favourable climate conditions, these nations have been able to harness their natural resources effectively to meet the increasing demand for food. Asian countries like China, India, Indonesia, Vietnam, Thailand, and Bangladesh have emerged as major players in aquaculture, contributing significantly to the world's aquaculture (Ahmed and Azra, 2022) (Fig. 1).

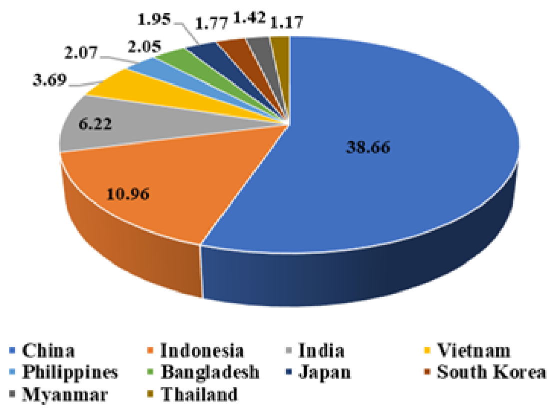

Fig. 1. Role of major Asian countries in aquaculture production (%) in 2020.

In the context of global food security, the role of Asian countries in aquaculture is of paramount importance (Mathias et al., 2020). As the demand for protein-rich aquafood continues to grow, their efforts to maintain sustainable practices and ensure responsible aquaculture are critical for meeting the nutritional needs of a growing population while safeguarding aquatic ecosystems.

Definition of Feed Additives

Feed additives are non-nutritive substances that are incorporated into animal feed in order to modify the physical or chemical characteristics of the feed, or to modify the performance or enhance the quality of the food-derived products (Barrows and Hardy, 2000). The idea of functional aquafeeds denotes a developing new strategy for creating fish and crustacean diets. These useful feed additives have the potential to replace chemotherapeutics and antibiotics (Yousefi et al., 2018). Phytogenic chemicals, organic acids, yeast products, immune system boosters, mycotoxin binders, probiotics, prebiotics, and enzymes are all examples of functional feed additives (Alemayehu et al., 2018).

Feed Additives as Antibiotics Alternatives

The principal application of antibiotics in aquaculture pertains to the treatment of water to mitigate the transmission of diseases. The overuse of antibiotics promotes the development of antibiotic-resistant bacteria, enabling them to survive and proliferate despite antibiotic treatments. (Anderson et al., 2003). Many of the same antibiotic compounds are used both to treat fish and human disease (Angulo, 2000). Because of this, there may be public health concerns if antibiotics are overused to treat aquatic animal species. For this reason, many nations have restricted the use of antibiotics in aquafeeds to promote fish growth (Chowdhury et al., 2022; Hoseinifar et al., 2024). The application of functional feed additives offers a potentially advantageous solution for augmenting growth performance and bolstering immune resilience in fish (Dawood et al., 2017) (Fig. 2).

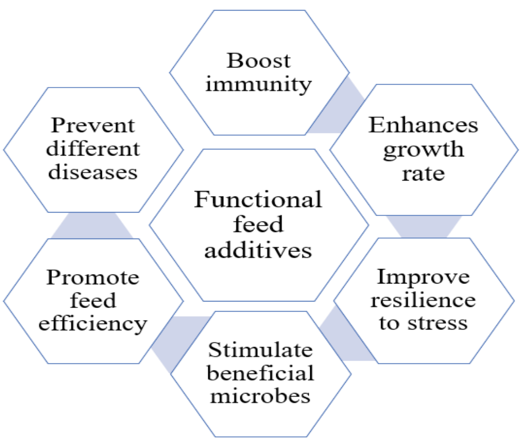

Fig. 2. Role of some functional feed additives in aquaculture production (adapted from Dawood, 2021).

Furthermore, it has been observed that immunostimulants have the potential to enhance the individual's ability to resist infectious diseases. The most commonly used alternatives to antibiotics include probiotics, prebiotics, plant extracts, organic acids, and enzymes. Since many feed additives are already have been researched, this review focuses on less traditional alternatives.

The current use of antibiotics in aquaculture

Some antibiotics have been used to control diseases of aquatic animal immune systems. Regulatory measures vary substantially from country to country, so current trends and net antibiotic usage in aquaculture are difficult to assess globally. Table 1 presents a compilation of permitted and reported antibiotics across major aquaculture-producing nations and organisations, based on data reported in various studies.

Aquatic animals' innate immune systems can be activated in two ways by environmentally friendly feed additives: i) the direct stimulation of the innate immune system, and ii) the promotion of commensal microbiota growth (Orso et al., 2022). Fish rely solely on their intrinsic immune response to combat pathogens, as their adaptive immune system is constrained in its ability to provide protection (Esteban et al., 2005) by the production of different cells and soluble components involved in immune responses. Lymphocytes, which encompass T cells, B cells, and large granular lymphocytes, as well as phagocytes like mononuclear phagocytes, neutrophils, and eosinophils, are various types of leukocytes that function as the initial barrier of the immune system (basophils, mast cells, platelets). The subsequent sections will provide a comprehensive account of the available information, elucidating the distinct methodologies and trends in the utilisation of functional feed additives in the field of aquaculture. The components of the fish innate immune system is shown in Figure 3.

It has been observed that certain feed additives possess the capacity to augment the non-specific immune response (Fig. 4). A recent study by Choi et al. (2023) has demonstrated the notable enhancement of non-specific immune parameters in fish as a result of incorporating four distinct functional feed additives. This finding underscores the potential of such additives to bolster the innate defence mechanisms of aquatic organisms, thereby contributing to the overall immune competence and health status of these species.

Feed Additives as a Tool for Sustainable Aquaculture

Aquaculture sustainability

Fish farming can help to provide subsistence and feed a global population that is likely to reach nine billion by

Table 1. List of approved antibiotics used in primary aquaculture producing nations across Asia.

Countries	Antibiotics authorised / reported / approved	References
China	13 antibiotics authorised: sulphamethazine, sulphamethoxazole, sulphamonomethoxine, thiamphenicol, oxolinic acid, sulphadiazine, trimethoprim, doxycycline, flumequine, neomycin, norfloxacin, enrofloxacin, and florfenicol	Wanyan et al. (2023)
Vietnam	30 antibiotics authorised: spectinomycin, tetracycline, tilmicosin, trimethoprim, tylosin, amoxicillin, benzylpenicillin , ciprofloxacin, cloxacillin, colistin, chlortetracycline, dicloxacillin, difloxacin, emamectin , erythromycin, flumequine, neomycin, oxolinic acid, ormetoprim , oxytetracycline, oxacillin, paromomycin, sarafloxacin, sulfadimethoxine, sulfadiazine, sulfamonomethoxine, sulfamethoxazole, sulfamethazine	Assis Magalhães (2021)
Thailand	14 antibiotics authorised: sulfadimethoxine, sulphamonomethoxine, sulfadimethoxine, sulphaguanidine, trimethoprim, tribrissen, tetracycline, amoxicillin, enrofloxacin, norfloxacin, oxytetracycline, ormetoprim, penicillin, sulfadiazine	Assis Magalhães (2021)
Bangladesh	12 antibiotics are reported: oxytetracycline, penicillin g, sulfadiazine, sulfamethazine, sulfamethizole, sulfamethoxazole, trimethoprim, tylosin, amoxicillin, chlortetracycline, doxycycline, erythromycin	Chen et al. (2020)
Japan	10 antibiotics reported: lincosamide, oxytetracycline, sulphamonomethoxine, sodium alkane sulfonate, amoxicillin, carbolic acid, doxycycline, erythromycin, fosfomycin, oxolinic acid	Chen et al. (2020)
Korea	20 antibiotics reported: cefovecin, cefquinome, ceftiofur, chlortetracycline, danofloxacin, doxycycline, enrofloxacin, erythromycin, kitasamycin, marbofloxacin, minocycline, oleandomycin, oxytetracycline, roxithromycine, sedecamycin, spiramycin, tetracycline, tilmicosin, tulathromycin, tylosin	Kim et al. (2014)
India	6 antibiotics reported: cephalexin, doxycycline, enrofloxacin, erythromycin, sulfamethoxazole + trimethoprim , tetracycline	Patil et al. (2022)
FAO	5 antibiotics approved: oxytetracycline, florfenicol premix, sarafloxacin, erythromycin, sulphonamides potentiated with trimethoprim or ormethoprim	Hernández Serrano (2005)

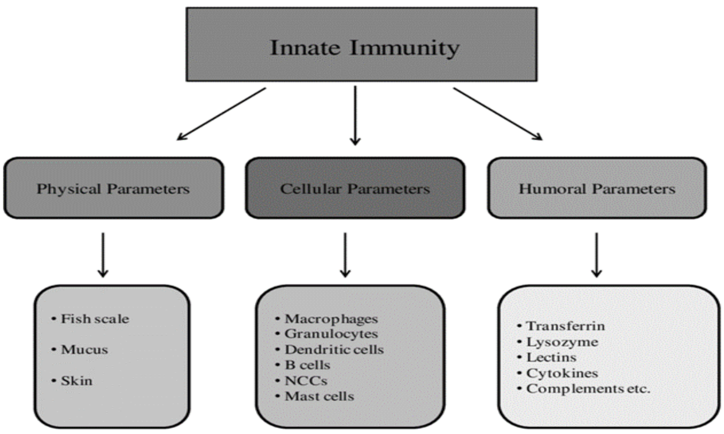

Fig. 3. Components of the fish innate immune system (from Kordon et al., 2018).

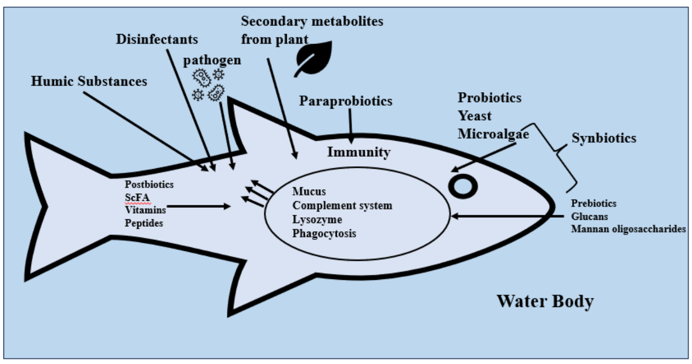

Fig. 4. Feed additives trigger immune response in fish (from Lieke et al., 2020).

2050, if it is practiced responsibly. Important principles of aquaculture sustainability include the following characteristics (FAO, 2022):

Environmental sustainability

Aquaculture should not significantly damage the environment, cause the loss of species, or have a significant influence on pollution.

Economic sustainability

Aquaculture has to be a profitable industry with promising long-term prospects.

Social and community sustainability

Aquaculture must be ethical and benefit the local area.

The role of feed additives in aquaculture sustainability

Sustainable aquaculture production can potentially feed a growing population and provide global economic benefits with minimal or no negative environmental impacts. Sustainability is a complex topic requiring multiple inputs and diverse perspectives for its resolution. The most popular certification programs are founded upon a framework consisting of seven primary categories. The topics of interest include genetics, legal compliance, social responsibility, land and water utilisation, water pollution and waste management, feed management, health medications and chemicals management. Feed supplements are a tool in sustainable aquaculture production that may be used to increase fillet quality, decrease the dependence on medicated treatments, and increase production efficiency. Feed additives can support the latter three for sustainable aquaculture development (Fig. 5).

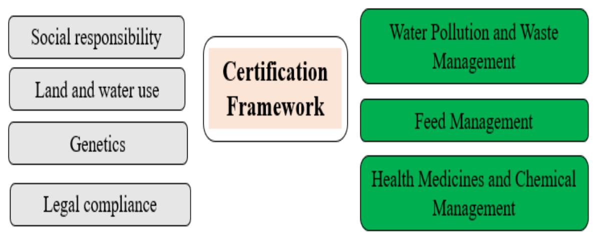

Fig. 5. Feed additives can support 3 of the 7 principles of certification (Gonçalves and Santos, 2017).

Effects and Role of Different Types of Feed Additives Used in Aquaculture

Probiotics

A probiotic refers to a cultured product or live microbial feed supplement that exerts a beneficial impact on the host by augmenting the microbiota within the intestinal tract (Fuller and Gibson, 1998). It increases the stability of the microflora in the gut, which in turn acts as an antimicrobial by secreting antibacterial compounds, prevent pathogen adhesion to the intestine, and producing some antitoxin effects. The mode of action of probiotics involves their ability to positively influence the gut microbiota by promoting the growth of beneficial bacteria (Hemarajata and Versalovic, 2013; Zhou et al., 2024). They enhance gut barrier function, modulate immune responses, and produce antimicrobial compounds, thereby improving digestion, nutrient absorption, and overall health in hosts (Fuller and Gibson, 1998; Latif et al., 2023) . It can also regulate the body's allergic response by influencing the immune system. Table 2 provides information regarding the utilisation of probiotics as additives in fish feeds and their corresponding effects.

Although probiotics offer many advantages, some researchers have reported concerns about the risk of introducing non-native or pathogenic strains that could disrupt local ecosystems or harm fish health (Didari et al., 2014; Goh et al., 2022) . The efficacy of probiotics can be inconsistent due to variations in environmental conditions, feed composition, and fish species. Additionally, maintaining the viability of probiotics during feed processing and storage can be challenging (Tripathi and Giri, 2014). Therefore, it is recommended to carefully select and monitor probiotic strains and optimise processing and storage conditions to ensure their efficacy.

Prebiotics

Prebiotics are carbohydrates that can be divided into monosaccharides, oligosaccharides, or polysaccharides based on the degree of polymerisation they have. Prebiotics may improve a variety of aquatic animals' biological responses and lessen pathogen-related mortality (Dawood and Koshio, 2016). Prebiotics are frequently utilised in aquaculture, including inulin, oligofructose, b-glucan, oligosaccharide, fructo-oligosaccharide and mannooligosaccharide. Prebiotics function primarily by selectively stimulating the growth and activity of beneficial bacteria in the gut (Davani-Davari et al., 2019). These non-digestible food components pass undigested through the upper gastrointestinal tract and are fermented by these beneficial bacteria in the colon. This fermentation process produces short-chain fatty acids (SCFAs) and other metabolites that help maintain gut health, improve intestinal barrier function, modulate immune responses, and potentially enhance mineral absorption (You et al., 2022). Thus, prebiotics contribute to overall gastrointestinal well-being and systemic health. The utilisation of prebiotics as additives in fish feeds and their corresponding impacts are presented in Table 3.

The efficacy of prebiotics can vary depending on fish species, diet composition, and environmental conditions

Table 2. Summary of probiotics and their effects on fish species.

Probiotics	Effects	References
Streptococcus faecium	Enhanced the protein and lipid content of Nile tilapia (*Oreochromis niloticus*) through growth optimisation	Lara-Flores et al. (2003)
Bacillus subtilis and *Streptomyces*	Improved growth and survival of the ornamental fishes (*Xiphophorus hellerii, Poecilia reticulata*	Dharmaraj et al. (2010)
Lactobacillus plantarum	Enhanced resistance of *Labeo rohita* against *Aeromonas hydrophila* infection	Giri et al. (2013)
Pseudomonas fluorescens	The mortality rate of rainbow trout (*Oncorhynchus mykiss*) weighing 40 g was observed to decrease when infected with the pathogenic bacterium *Vibrio anguillarum*	Gram et al. (1999)

Table 3. A summary of the effects of different prebiotics on fish species documented in the literature.

Prebiotics	Effects	Fish species	References
Inulin	Increase growth, lysozyme activity and butyric acid	*Oreochromis niloticus, Pseudoplatystoma reticulatum, Pelteobagrus fulvidraco*	Yones et al. (2020); Ghafarifarsani et al. (2021); Oliveira et al. (2022); Li et al. (2023)
Fructooligosaccharides (FOS)	Increase growth performance	*Oncorhynchus mykiss*	Ortiz et al. (2013)
β-glucan	Increase growth 0.1 % and immune system 0.2 %	*Trachinotus ovatus, Rutilus rutilus, Hyphessobrycon eques*	Hoang (2020); Kazuń et al. (2020); Furlan-Murari et al. (2022)
Arabinoxylan oligosaccharide (AXOS)	Enhance survival rate and phagocytic activity	*Acipenser baerii*	Geraylou et al. (2012)
Mannanoligosaccharide (MOS)	Enhance growth, white blood cell count, phagocytic activity and gene expression	*Labeo rohita, Oreochromis niloticus*	Abu-Elala et al. (2018)
Galactooligosaccharide (GOS)	Increase the immune system	*Cyprinus carpio*	Pietrzak et al. (2020)
Oligosaccharides	Increase survival rate	Sex-reversed red tilapia (*Oreochromis niloticus × Oreochromis mossambicus*)	Plongbunjong et al. (2011)
Fructooligosaccharide (FOS)	Increase growth performance	*Salmo salar, Oncorhynchus mykiss*	Ortiz et al. (2013); Dhanasiri et al. (2023)
Galactoglucomannan (GGM)	Increase growth by increasing microvilli heights in pyloric caeca and increased immunity response	*Sciaenops ocellatus*	Zhou et al. (2010)
Isomaltooligosaccharide (IMO)	Enhance growth performance	*Clarias gariepinus*	Romano et al. (2018)
Xylooligosaccharide (XOS)	Increase growth rate, microvilli height, lipase and amylase activity	*Dicentrarchus labrax, Oncorhynchus mykiss*	Abdelmalek et al. (2015); Wang et al. (2022)

(Amillano-Cisneros et al., 2023). Additionally, high inclusion levels may lead to digestive disturbances or nutrient imbalances in fish.

Phytogenic compounds

Fish diets often contain phytogenic chemicals, which are derived from plants and are thought to boost fish health and growth. The utilisation of these plant compounds has been associated with a diverse range of advantageous effects, such as antioxidant, antibacterial, anticarcinogenic, antiparasitic, appetite enhancement (e.g. growth promotion), and stimulation of bile secretion and digestive enzyme activity (Asimi and Sahu, 2013). Phytogenic compounds as feed additives for fish exert their effects through several mechanisms. Firstly, they often contain bioactive components such as polyphenols, terpenoids, and essential oils that possess antimicrobial and antioxidant properties. These compounds can help maintain a healthy gut microbiota by inhibiting the growth of pathogenic bacteria and promoting the growth of beneficial bacteria (Yang et al., 2015). Secondly, phytogenics can modulate the immune system of fish, enhancing their ability to resist infections and reducing inflammation (Firmino et al., 2021). Additionally, they may improve nutrient utilisation and digestion efficiency in fish, thereby promoting better growth performance and overall health (Gonçalves and Santos, 2015). There are many phytogenic substances utilised in aquaculture summarised in Table 4.

Table 4. Effects of different phytogenic compounds on fish species.

Phytogenic compounds	Effects	Fish species	References
Rosmarinus officinalis	The mortality rate caused by *Streptococcus iniae* in Nile tilapia is found to be reduced	*Oreochromis niloticus*	Zilberg et al. (2010)
Psidium guajava	Tilapia infections caused by *Aeromonas hydrophila* can be prevented with the use of *Psidium guajava*'s dry leaf powder and ethanol extract	*Oreochromis niloticus*	Pachanawan et al. (2008)
Ipomoea batatas	Nile tilapia grew faster and used food more efficiently when their diet included sweet potato peel	*Oreochromis niloticus*	Omoregie et al. (2009)
Essential oils (*Oregano oils*), potassium sorbate encapsulated with palm oil and soya oil	Enhances the fish growth performance and protection against *Aeromonas hydrophila*	*Oreochromis niloticus*	Abo-State et al. (2017)
limonene and thymol	No growth effect was observed	*Oreochromis niloticus*	Aanyu et al. (2020)
Paulownia leaf extract	It enhanced the survival percentage and diminished the development of all gram-negative intestinal microbial content	*Oreochromis niloticus*	El-Refiae et al. (2024)

Several researchers reported that the quality and potency of plant extracts can vary significantly based on plant species, growing conditions, and extraction methods (Bolouri et al., 2022; Mbokane and Moyo, 2022; Orso et al., 2022). They may also interact with other feed components, which can reduce their efficacy or cause unexpected side effects. Moreover, high doses might lead to palatability issues, impacting feed intake and potentially causing adverse health effects in fish (Kaushik and Hemre, 2008).

Organic acids

Organic acids encompass a group of weak carboxylic acids, including formic, citric, benzoic, and lactic acid, which are characterised by their short-chain fatty acid structure and volatile nature (Bai et al., 2015). In the gastrointestinal tract of aquatic organisms, the growth of Gram-negative bacteria is hindered by the presence of organic acids. These acids are able to permeate the bacterial cell wall, subsequently entering the interior of the cell and impeding its growth (Bai et al., 2015). Table 5 presents the impact of organic acids and their salts on various fish feeds.

Organic acids in fish feed act by lowering the pH of the gastrointestinal tract, inhibiting pathogenic bacteria, and enhancing nutrient absorption and digestive enzyme activity (Chen et al., 2024). They also modulate gut microbiota, boost immune response, and can serve as an energy source for intestinal cells, overall improving fish health and growth performance (Busti et al., 2020). But using the wrong type or dosage of organic acids can lead to no beneficial effects or even detrimental impacts on fish growth and physiology (Ng and Koh, 2018).

Table 5. The impact of diverse organic acids and their influence on fish species.

Organic acids and salts	Effects	References
Formic acid	The inclusion of formic acid in the diet of rainbow trout resulted in a noticeable enhancement in the digestibility of phosphorus.	Vielma and Lall (1997)
Citric acid	Improved growth performance, nutrients digestibility on *Labeo rohita*	Iqbal et al. (2021)
sodium diformate	Including a protein supplement of 0.3 % into tilapia fingerlings' diets increased their protein efficiency ratio and protein retention	Liebert et al. (2010)
Potassium diformate	Enhanced growth performance, pancreatic protease and lipase activities, digestibility, survival rate and immunity	Chen et al. (2024)
Formic acid, acetic acid and butyric acid	No impact on feed utilisation and survival on *Clarias gariepinus*	Asriqah et al. (2018)
Fumaric Acid	Improved growth, feed efficiency, protein use, and intestinal villi morphometry on Nile tilapia	Das Neves et al. (2021)
Butyric acid	Improved fish growth and did not pose any negative impact on carcass quality of *Clarias gariepinus* and *Oreochromis niloticus* fingerlings	Omosowone et al. (2018)

Mycotoxin binders

The term "mycotoxins" refers to the secondary metabolites that are produced by many types of fungi (Binder, 2007). Mycotoxins in the designed feed can have a negative impact on plant-based feed ingredients, resulting in diminished weight increase and decreased feeding efficiency, which in turn can damage the fishes' livers and kidneys. Aflatoxins are primarily derived from fungal species such as *Aspergillus flavus*, *A. parasiticus*, and *Fusarium* spp. Additionally, mycotoxins pose significant risks in the context of aquaculture feeds (Manning, 2015). One can use a variety of binders to neutralise the effects of these mycotoxins. Typically, animal feeds consist of aluminium silicates, bentonite, montmorillonite, hydrated sodium calcium alumina silicates, and zeolitic minerals, with quantities ranging from 1 to 10 grams per kilogram (Binder, 2007). Effects of mycotoxin binders in different fish feeds are given in Table 6.

Mycotoxin binders in aquaculture reduce mycotoxin levels, enhancing fish health, growth performance, and immunity by preventing immunosuppressive effects and maintaining liver and kidney functions (Selim et al., 2014; Manning, 2015; Wang et al., 2016). However, they may also bind essential nutrients, potentially causing deficiencies, and their cost can increase feed production expenses. Additionally, their efficacy can vary based on the type and concentration of mycotoxins and specific aquaculture conditions.

Enzymes

Enzyme supplements, such as phytase, carbohydrase, protease, lipase, alpha-amylase, papain, and pepsin, are commonly incorporated into aquafeeds. Enzymes used as feed additives in fish aquaculture work by breaking down anti-nutritional factors in feed ingredients, improving nutrient digestibility and absorption (Liang et al., 2022). The majority of the phosphorus found in plant seeds is phytate, accounting for 80 % of the total (Shanmugam, 2018). Low levels of phytate phosphorus digestibility and bioavailability mean that they are not a good source of nutrition for fish. Therefore, phytase in fish feed promotes the digestion of phytate phosphorus, decreases phosphorus excretion, and also increases the use of both protein and phosphorus (Cao et al., 2007). Table 7 provides a comprehensive overview of the various applications of enzymes in different types of fish feeds.

Table 6. Effects of different mycotoxin binders on fish species.

Mycotoxin binders	Effects	References
Hydrated sodium calcium alumina silicates	The toxicity of aflatoxin B1 in Nile tilapia was significantly mitigated	Selim et al. (2014)
Bentonite	Pangasius catfish growth and AFB1 suppression results improved	Gonçalves et al. (2018)
Montmorillonite + Bentonite (Clay adsorbents)	The biochemical, histochemical parameters of fish fed 5 $g.kg^{-1}$ of clay adsorbents show remarkable improvement	Hassan et al. (2010)

Table 7. Effects of different enzymes and their effects on fish and shrimp.

Enzymes	Effects	References
Phytase	It increases growth, feed conversion ratio, protein efficiency ratio, and specific growth rate in Nile tilapia	Liebert and Portz (2005)
Alpha-amylase	It improved the starch digestibility in juvenile silver perch	Stone et al. (2003)
Pepsin, papain, amylase	Enhanced the growth and feed utilisation efficiency in Nile tilapia fingerlings	Alemayehu et al. (2018)
Proteases	Enhanced the growth and feed utilisation efficiency in Nile tilapia, rainbow trout, gibel carp and white shrimp	Dalsgaard et al. (2012); Li et al. (2016, 2019)
Sodium acetate	Increase growth and feed utilisation of large yellow croaker	Luo et al. (2020)
Fungal cellulase	Increase growth rate of *Labeo rohita*	Ranjan et al. (2018)
Microencapsulated organic acid	Increase growth and survival rate of *Litopenaeus vennamei*	Chowdhury et al. (2021)

Although enzymes have some beneficial impacts, potential degradation of enzyme activity during feed processing and storage, and the possibility of inconsistent efficacy due to variations in feed composition and fish species is major concern. Additionally, improper dosage may lead to suboptimal benefits or digestive disturbances in fish.

Seaweeds

Seaweeds are macroalgae, and their derivatives have been utilised in the composition of aquaculture feed.

Seaweed provides bioactive compounds like polysaccharides, antioxidants, vitamins, and minerals, which boost immune response and improve gut health (Sobuj et al., 2021; Islam et al., 2023). Seaweeds also contain prebiotic fibres that promote beneficial gut microbiota, enhancing nutrient absorption and digestion (Shannon et al., 2021). Additionally, their anti-inflammatory and antimicrobial properties help protect fish from diseases and stress (Dip et al., 2024). In fish nutrition, minerals and polysaccharides found in seaweeds and their derivatives are used as functional feed additives. In addition to increasing triglyceride and protein deposition in muscle, seaweed promotes weight gain (Fleurence et al., 2012). Seaweed species such as *Ulva* sp., *Undaria* sp., *Ascophyllum* sp., *Porphyra* sp., *Sargassum* sp., *Gracilaria* sp., and *Laminaria* sp. are widely studied and used for feed formulation for the fish diet.

While seaweed offers significant benefits, it's important to choose the right species because nutritional content can vary based on species and harvesting conditions (Islam et al., 2023). There's also a risk of contaminants, such as heavy metals and pollutants, from the marine environment (Filippini et al., 2021). Furthermore, incorrect inclusion rates can result in dietary imbalances and digestive issues in fish. Application of seaweeds in different fish feeds and its effects is shown in Table 8.

Yeast products

Yeast contains several enzymes, fatty acids, amino acids, vitamin B-complex, and unidentified growth agents. The most widely commercialised species is *Saccharomyces cerevisiae*, known as "baker's yeast". Yeasts are predominantly employed in the food industry for the purpose of generating ethanol and carbon dioxide in the processes of baking, brewing, and wine fermentation. Marine yeasts are actively involved in the decomposition of plant substrates, biodegradation of oils, parasitic interactions, and the recycling of nutrients (Kutty and Philip, 2008; Alamillo et al., 2017; Doan et al., 2023). Other yeasts, such as Torula yeast, are also increasingly being tested and applied as feed additives. It has been established that yeasts can boost the development, survival, and maturation of finfish and crustaceans, as well as their immune and antioxidant systems. Glucan, mannoproteins, chitin (as a minor component), and nucleic acids are the primary immune-stimulatory components of yeast (Meena et al., 2013). Effect of yeast additives in different fish feeds are given in Table 9.

Table 8. Application of seaweeds in different fish and shrimp feeds and its effects.

Seaweeds or its derivatives	Effects	References
Gracilaria spp., *Ulva* spp., or *Fucus* spp.	In European seabass, it boosted their lipase, antioxidant, alternative complement, and lysozyme activities.	Peixoto et al. (2016)
Low-molecular-weight agar	Specific growth rate, feed conversion ratio, phagocytosis, red blood cell count, and resistance against *Aeromonas hydrophila* all improve in basa fish (*Pangasius bocourti*) when 2 $g.kg^{-1}$ is added to their diet	Doan et al. (2014)
Red seaweed (*Catenella repens*)	It has impact on pond water quality, shrimp growth, feed conversion ratio, shrimp survival, pigmentation.	Banerjee et al. (2010)
Sargassum angustifolium	It improved growth and feed utilisation of *Oncorhynchus mykiss*	Zeraatpisheh et al. (2018)
Padina gymnospora	It increased the survival rate of *Cyprinus carpio*	Rajendran et al. (2016)
Hypnea musciformis	It improved growth and survival rate of *Oreochromis niloticus*	Kiadaliri et al. (2020)
Sargassum cristaefolium	No significant effect was found for *Litopenaeus vannamei*	Jahromi et al. (2021)

Table 9. Effects of different yeast products on fish, shrimp and sea cucumber.

Yeast products	Effects	Reference
Saccharomyces cerevisiae	It strengthened bacterial resistance to infections and illness in hybrid striped bass, *Epinephelus coioides, Oreochromis niloticus, Pseudobagrus ussuriensis*	Li and Gatlin (2004); Yang et al. (2020); Islam et al. (2021); Hou et al. (2022)
Saccharomyces boulardii	It increased the activity of brush border enzymes and gut microbes in rainbow trout	Encarnação (2016)
Yeast β-glucans	Modulate the innate immune system of fish and shrimp and improve their survival	Meena et al. (2013)
Rhodotorula sp.	It showed better growth in juvenile sea cucumber, *Apostichopus japonicus*	Ma et al. (2019)

Appropriate dietary supplementation of yeast extract can enhance growth performance, digestibility, and antioxidant capacity in fish (Sun et al., 2024). However, improper processing or storage may lead to contamination, loss of beneficial properties, and the potential introduction of pathogens, reducing the additive's effectiveness.

Future Research and Trends

The incorporation of the feed additives described in this review has ushered in a new era in the field of aquafeeds. Aquatic animals are commonly recognised as viable alternatives for enhancing the welfare and productivity of aquatic organisms, while also contributing to overall financial profitability. Probiotics, prebiotics, immunostimulants, medicinal herbs, and organic acids are viable options for establishing and sustaining an optimal equilibrium of advantageous microflora within the gastrointestinal tract. Significant progress has been made in the cultivation of aquatic animals through the initial utilisation of antibiotics. However, this approach has raised concerns regarding the emergence of microbial resistance, because of their indiscriminate application.

The incorporation of feed additives into a regular supplementation protocol has gained widespread popularity in the aquafeed industry, especially as a post-antibiotic treatment strategy. The utilisation of feed additives presents numerous potential advantages, such as the alteration of host metabolism, stimulation of the immune system, improved absorption of nutrients, prevention and suppression of pathogens in the intestinal tract, enhanced performance, and ultimately reduced risk to human health. Further research is required to examine the expression of antimicrobial peptides in aquatic animals induced by functional feed additives. It would be of interest to learn more about the additional beneficial mechanisms of these substances. Furthermore, by utilising genetic engineering techniques, it becomes feasible to enhance or develop entirely new feed additives that possess significant potential in the field of oral immuno-therapeutics.

Conclusion

This study presents an overview of feed additives with the aim of identifying effective alternatives to antibiotics, and as immunostimulant and growth promoters for sustainable aquaculture development. The Blue Revolution is taking place to meet the increasing demand for food and protein resulting from population expansion. The projected growth in aquaculture highlights the need for effective, natural solutions for aquaculture producers. The above-mentioned feed additives may offer naturally occurring solutions for aquaculture producers that contributes to sustainable aquaculture by supporting profitability, feed efficiency, immunity, enhanced resistance to infectious disease and general animal health. Collectively, they have the potential to minimise reliance on antibiotics. Furthermore, it should be noted that functional feed additives possess environmentally friendly characteristics and are unlikely to exert detrimental effects on the aquaculture industry. So, feed additives are added to feed to promote growth and biomass produced, as well as to make diets more attractive, palatable, and digestible - via attractants, tastes, and elements that increase digestibility.

However further research work is required to optimise effective applications in aquaculture. From this study, natural feed additives have a strong potential to induce a range of beneficial effects as feed supplements, supporting growth and immune function in cultured aquatic organisms.

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