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Functional Feed Additives: A Sustainable Strategy for Aquaculture

Sneha Sathyan G[1], Pralipta Priyanjali Panda[2] Subhransu Mohapatra[3]*

[1]Ph.D. Scholar, Division of Aquaculture, ICAR–Central Institute of Fisheries Education (ICAR-CIFE), Mumbai, India
[2]Assistant Fisheries Officer, FARD, Government of Odisha, India
[3]Young Professional II, NSPAAD, College of Fisheries, OUAT, Odisha, India – 760007

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*Corresponding Author
Subhransu Mohapatra*

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INTRODUCTION

Aquaculture fastest growing industry in the world with significantly contributing food security, nutrition and livelihood of millions of population. The aquaculture production highest value about 130.9 MMT, exceeding the capture production (Sofia, 2024). In aquaculture feed representing 50 – 60 % of production cost. During feed manufacturing, feed additives are incorporated to improve the nutritional quality of the feed, support fish health and performance, and optimize feed conversion efficiency. Most of the feed additives are non nutritious and include antioxidants, immunostimulants, probiotics, antibiotics are added to improve the growth as well as water quality Unlike conventional dietary components functional feed additives exert specific physiological effect that enhance animal health and production efficiency. Currently unrestrained use of antibiotic and chemicals in aquaculture leads to issues such as antimicrobial resistence, pollution to environment (Caputo et al., 2023). On account of this functional feed additives have emerged as sustainable alternatives for improving fish health and maintaining production while minimizing environmental impacts.

2. Functional feed additives

The functional feed additives are included in feeds to provide specific benefits to cultured fish, these are supplements that provide growth and health benefits beyond basic nutrition. Functional feed additives improve animal health performance, immune response, and overall wellbeing of animals. These feed additives are sourced from various origins and are eco-friendly for both fish and the aquatic environment.

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The functional feed additives include probiotics, prebiotics, seaweed, microalgae, organic acids, mycotoxin binders, phytobiotics, mushrooms, and yeast (Onomu et al., 2024). Consequently, the development and adoption of functional feeds has become a major focus of modern aquaculture nutrition, aiming to improve animal welfare while reducing dependence on antibiotics and other chemotherapeutic agents.

Advantages of functional feed additives

- Increased beneficial bacteria in gut
- Increased feed efficiency and survival
- Improved growth and immunity of organism
- Reduced dependency on antibiotics and chemical
- Reduced environmental pollution

2.1 Probiotics

Probiotics are live microorganisms incorporated into aquafeeds to enhance fish growth through the regulation of the intestinal microbial flora. Probiotics may be a single species of microorganisms or a mixture of species. Probiotics possess antimicrobial activity by maintaining the stability of the intestinal microbes, producing antibacterial compounds such as bacteriocins and organic acids, inhibiting pathogen adhesion through competitive exclusion, and competing with harmful microorganisms for essential nutrients, overall they promote growth and survival of cultured organism (Bharathi et al., 2019).

Growth promoter	Bacillus sp. S11 Bacillus coagulans	Peneaus monodon Cyprinus carpio koi
Pathogen inhibition	Saccharomyces cerevisiae S. exiguous Bacillus sp.	Litopenaeus vannamei
Stress tolerance	Lactobacillus delbrueckii	Dicentrarchus labrax

2.2 Prebiotics

1. Prebiotics are non digestible carbohydrates that serves as food to the beneficial microorganisms in a host digestive system. Several prebiotics, including inulin, oligofructose, XOS, FOS, MOS, GOS, and β-glucans, are routinely employed in aquaculture to promote intestinal health and overall productivity. Prebiotics improves intestinal health by increasing villus height, strengthens the mucosal barrier, and stimulating digestive enzyme activity thereby enhancing nutrient digestion and feed utilization. They also modulate the immune system by activating macrophages, enhancing phagocytosis activity (Crittenden et al., 2009; Gibson et al., 1995)

2.3 Phytobiotic

Phytobiotic compounds, obtained from plant sources, are incorporated into aquafeeds to enhance growth performance, immunity, and overall fish health. They originate from leaves, roots, tubers, or fruits of herbs, spices, or other plants. They are available either in a solid, dried, or ground form, as extracts or essential oils. These plant-derived products possess a wide range of biological properties, including antioxidant, antimicrobial, anticarcinogenic, analgesic, insecticidal, antiparasitic, growth-promoting, and appetite-enhancing activities (Zhou et al., 2010; Volpatti et al., 2013).

2.3.1 Major phtogenic compounds in aquaculture

Picrorhiza kurroa

Employed as antistress compound for shrimps. It can inhibit the generation of oxygen anions and to scavenge free radicals.

Ashwagandha (*Withania somnifera)*

Ashwagandha contain withanolides, a group of steroidal lactones. It possesses adaptogenic properties, including anti-stress, antioxidant, immunomodulatory, and rejuvenating effects.

Neem (*Azardirachta indica)*

They participate in stress-induced suppression of gamma glutamyl transpeptidase activity in lymphoid tissues such as the spleen, thymus, and macrophages.

Toona sinensis

Rutin, a naturally occurring bioflavonoid obtained from plant sources, has demonstrated potent antioxidant and stress-mitigating effects in crustaceans.

Plant source	Major bioactive compounds	Benefits in aquaculture
Turmeric (*Curcuma longa)*	Curcumin	Improves immunity, antioxidant activity, growth, disease resistance
Garlic (*Allium sativum*)	Allicin	Antibacterial, antiparasitic, appetite stimulant, growth promoter
Neem (*Azadirachta indica*)	Azadirachtin, nimbin	Antimicrobial, immunostimulant, antiparasitic
Moringa (*Moringa oleifera*)	Flavonoids, phenolics, vitamins	Enhances growth, immunity, antioxidant status
Tulsi (*Ocimum sanctum*)	Eugenol	Antioxidant, stress reduction, immune enhancement
Ginger (*Zingiber officinale*)	Gingerols, shogaols	Improves digestion, feed utilization, immunity
Aloe vera	Aloin, polysaccharides	Immunostimulant, gut health, wound healing
Fenugreek (*Trigonella foenum-graecum*)	Saponins, flavonoids	Improves growth and digestive enzyme activity
Amla (*Phyllanthus emblica*)	Vitamin C, tannins	Antioxidant, immune booster
Cinnamon (*Cinnamomum verum*)	Cinnamaldehyde	Antibacterial, antioxidant
Black pepper (*Piper nigrum*)	Piperine	Enhances nutrient absorption and digestion

2.4 Seaweeds

Seaweeed also known as marine macroalgae, are increasingly recognised as valuable functional feed additives due to their rich content of bioactive compounds . They conatin active metabolites such as alginate, laminarin, fucoidan, carrageenan and polyphenols, carotenoids, vitamins, minerals, essential amino acids, omega-3 fatty acids, and antioxidants which enhances growth performance, feed efficiency, immunity, disease resistance, antioxidant capacity, stress tolerance, and gut health. Seaweed-based feed additives have emerged as natural alternatives that promote animal welfare while minimizing environmental impacts (Holdt & Kraan, 2011; Morais et al., 2020).

Seaweed group	Major bioactive compounds	Functional properties
Brown algae (Phaeophyceae)	Fucoidan, laminarin, alginate, phlorotannins	Immunostimulant, antioxidant, antimicrobial, prebiotic
Red algae (Rhodophyta)	Carrageenan, agar, phycoerythrin	Antiviral, antioxidant, immunomodulatory
Green algae (Chlorophyta)	Ulvan, chlorophyll, carotenoids	Prebiotic, antioxidant, growth promoter

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2.5 Mycotoxin binders

Mycotoxin binders are non-nutritive feed additives incorporated into aquafeeds to reduce the adverse effects of mycotoxins by preventing their absorption in the gastrointestinal tract. Mycotoxins, produced primarily by fungi such as *Aspergillus*, *Fusarium*, and *Penicillium*, frequently contaminate plant-based feed ingredients including soybean meal, maize, wheat, rice bran, cottonseed meal, and groundnut cake (Manning et al., 2015). Their ingestion can impair growth, feed efficiency, immunity, reproductive performance, and organ function, particularly affecting the liver and kidneys of cultured fish and shrimp. As the aquaculture industry increasingly relies on plant-derived feed ingredients, the use of mycotoxin binders has become an effective strategy to improve feed safety and maintain animal health (Binder et al., 2007; Kumar et al., 2006). The mycotoxin binders such as Aluminium silicates, bentonite, montmorillonite, hydrated sodium calcium alumina silicates, Zeolitic materials are commonly used at the range of 1 to 10g/kg in the feeds.

2.6 Organic acid

Organic acids are weak carboxylic acids consisting of short-chain fatty acids, including formic acid, citric acid, benzoic acid, lactic acid, acetic acid, propionic acid, malic acid, sorbic acid, and their corresponding salts. In aquaculture, organic acids are used as functional feed additives to improve fish growth performance, nutrient utilization, and disease resistance. They reduce the pH of the gastrointestinal tract, thereby enhancing digestive enzyme activity and nutrient digestion. Additionally, organic acids can penetrate bacterial cell membranes, interfere with cellular processes, and inhibit the growth and proliferation of pathogenic microorganisms (Ng et al., 2017).

2.7 Enzymes

Enzymes as functional feed additives improve nutrient digestion and feed utilization by breaking down complex feed components into simpler, absorbable forms. Supplementation with enzymes such as phytase, pepsin, papain, amylase, glucanase, pentosanase, cellulase, and xylanase has been shown to enhance growth performance, feed conversion ratio (FCR), protein efficiency ratio (PER), specific growth rate (SGR), and nutrient digestibility in several aquaculture species. Phytase improves phosphorus availability, protein utilization, and energy retention by hydrolyzing phytate, while amylase enhances starch digestion. Proteolytic enzymes such as pepsin and papain improve protein digestion and feed utilization. Similarly, carbohydrases including glucanase, cellulase, pentosanase, and xylanase increase the digestibility of plant-based ingredients, improve nitrogen retention, and reduce ammonia excretion, thereby promoting better growth, feed efficiency, and environmental sustainability in aquaculture (Zheng et al., 2020; Ahmed et al., 2025).

3. Challenges Associated with Functional Feed Additives

Despite their numerous benefits, functional feed additives have certain limitations that needs to be addressed. The inclusion of bioactive ingredients often increases feed formulation costs, leading to higher overall production expenses. Furthermore, the stability and efficacy of some functional feed additives may be adversely affected by environmental factors, including elevated temperature, moisture levels, and prolonged storage duration, which may reduce their stability and shelf life. Proper dosage is also critical, as excessive inclusion levels can adversely affect feed palatability and reduce feed intake, whereas insufficient levels may fail to produce the desired physiological or health benefits. Furthermore, the adoption of functional feeds may be influenced by market acceptance, which depends on factors such as cost-effectiveness, consumer awareness and regulatory approval.

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CONCLUSION

Functional feed additives have become a major component of modern in aquaculture owing to their capacity to enhance growth-related performance parameters, improve feed utilisation, strengthen immune responses, and resistance to infectious diseases. Their application supports sustainable aquaculture by reducing reliance on antibiotics and chemicals while promoting animal health and production efficiency. The successful development of functional feeds requires a thorough understanding of the interactions between feed additives, the gastrointestinal microbiota, and the physiological and metabolic processes of cultured species. Although most functional feed additives are environmentally friendly and contribute to sustainable production, further research is needed to optimise their inclusion levels, evaluate long-term effects, and understand their mechanisms of action under different farming conditions.

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