Novel additives in aquafeed and their role in cost-effective feed and feeding management

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Introduction

Aquafeed constitutes a massive portion (around 50 to 70%) of total operational costs in aquaculture. Intensified aquaculture systems targeting enhanced production capacity have exaggerated the demand for both aquafeed additives. Conventional aquafeed resources often face issues like limited availability and varying costs due to market fluctuations and trade impacts (Van Riel *et al.,* 2023). Despite the rising prices, their supply remains active for now. However, a consistent availability seems uncertain for the rising future demands. Consequently, the industry is actively exploring the options to shift towards novel functional additives of animal or plant origin to optimize feed utilization and reduce costs. These additives are intended to address potential challenges associated with incorporating non-conventional ingredients into aquafeed, including variations in pellet structure and stability, feed composition, feed acceptance by the animals, as well as impacts on nutrient digestibility and absorption (Niu *et al.,* 2023).

Feed additives are non-nutritive substances incorporated into aquafeeds around 2% to enhance feed performance, availability and nutrient assimilation of the primary feed ingredients (Mustafa and Al-Faragi, 2021). Fish feed additives can also be categorized either as nutritive or non-nutritive feed additives based on their dietary value supplementation capacity (Varangia and Yadav, 2023). At present, a new classification of additives collectively called functional feed additives (FuFA's), which support health benefits beyond satisfying basic nutrient requirements, are being studied (Onomu and Okuthe, 2024). Regular aquafeed additives, including vitamins, mineral mixtures, amino acid mixtures, carotenoids, n-3 PUFAs and other singular chemical moieties, act as supplements for providing basic nutrition and improving the health and stress resilience of animals. Others are non-nutrient compounds, such as probiotics, prebiotics, organic acids, essential oils, and plant extracts, that do not provide nutrition directly but help improve health benefits by modulating various physiological responses.

Along with their role in supplementing major feed ingredients, these novel feed additives are explored for their potential to be metabolic modifiers, attractants, immunostimulants, etc., in aquafeeds (Dawood *et al.,* 2018). Also, several chemicals and antibiotics have been used previously to enhance animal health and combat infections in the aquaculture systems. To minimize these antibiotic usage in aquafeeds, a variety of non-conventional additives, such as essential oils, phytobiotics, and fermented products, have been studied recently for their efficacy in enhancing nutrient supplementation and animal health without reliance on antibiotics and other chemicals (El-Hack *et al.,* 2020).

These additives include:

• Functional amino acids and Nucleotides: Amino acids that play roles beyond protein synthesis, such as enhancing immunity. Methionine enhances growth and protein synthesis while supporting antioxidant defence mechanisms. Arginine boosts immune responses and aids in wound healing. Tryptophan can reduce stress and aggression in fish, promoting better welfare at 1–3% inclusion. Taurine inclusion at 0.1–1%, particularly in carnivorous fish diets, enhances metabolism. Glutamine improves gut health, nutrient absorption and stress resistance at 0.5–2%. Methionine and lysine are often supplemented at 0.5–2% to balance essential amino acid profiles in plant-based diets (Hossain *et al.,* 2024; Kolmakov and Kolmakova, 2020; Encarnação, 2016). Nucleotides, the building blocks of nucleic acids, support the immune function and growth in fish (Pelusio *et al.,* 2023). Synthetic nucleotides at 0.05–0.3% dietary inclusion can provide targeted benefits like improved chemoattraction, feed intake, gut health and stress resistance.

• Animal protein hydrolysates: Among these, the primary

additive is fish protein hydrolysates (FPH). Derived from fish by-products like trimmings, heads, and frames, FPH is rich in bioavailable peptides and amino acids. It enhances growth and immunity in aquaculture species. Processed animal proteins (PAP's) are also a viable non-conventional source, including poultry, feather, and blood meals. These are sustainable alternatives to fishmeal, providing high protein content (Hossain *et al.,* 2024). These hydrolysates improve digestibility, gut health, and feed efficiency, making them valuable alternatives to traditional protein sources. FPH is included in aquafeeds from 2-20%, whereas PAP's are allowed up to 2-8% depending on culture species and diet formulation (Woodgate et al., 2022). The latest novel additives include derivatives from krill, tunicates and polychaetes due to their desirable nutritional attributes. Also, authorized products derived from the insect species such as *Hermetia illucens* (Black Soldier Fly), *Musca domestica* (common housefly), *Alphitobius diaperinus* (Lesser Mealworm), *Tenebrio molitor* (Yellow Mealworm), *Gryllodes sigillatus* (Banded cricket), *Acheta domesticus* (House cricket), and *Gryllus assimilis* (Field cricket) are portrayed as the latest promising additives in aquafeeds formulation. Several studies suggest that including these hydrolysates in low fish meal diets can enhance growth performance, similar to higher fish meal diets (Swanepoel and Goosen, 2018; Leduc *et al*., 2018).

• Nano-mineral additives: Nanotechnology introduces nano-sized additives that improve nutrient delivery and absorption (Dube, 2025). Nano-minerals, including nano forms of selenium, zinc, and iron, have shown improved bioavailability, enhancing fish's growth and antioxidant status (Bhagat and Singh, 2022). Also, nano-encapsulation includes encapsulating feed additives at the nanoscale that protect them from degradation, ensuring targeted release and improved efficacy. Their inclusion levels vary based on species, formulation, and regulatory guidelines (Mohanta, 2024).

• Nano-zinc oxide (ZnO) inclusion at 0.01–0.1% improves growth and antioxidant defence.

• Nano-selenium (Se) at 0.005–0.05% enhances immune response and stress tolerance.

• Nano-iron (Fe) at 0.01–0.05% for improved oxygen transport and metabolism.

• Nano-copper (Cu) inclusion at 0.005–0.02% supports enzymatic functions and feed efficiency.

• Nano-calcium and magnesium are used at 0.05–0.2% to improve skeletal development and metabolic balance.

• Probiotics and Prebiotics: Live beneficial microorganisms that improve gut health and disease resistance (Lim et al., 2023). These probiotic strains colonize the fish gut, synthesize extracellular enzymes such as proteases, amylases, and lipases, and provide growth factors such as vitamins, fatty acids, and amino acids. Lactic acid bacteria such as *Lactobacillus-sp., Bacillus-sp.*, and *Enterococcus-sp*. are included at 0.05–0.5%, depending on strain efficacy and yeast, *Saccharomyces cerevisiae* included at 0.1–0.3% for improved digestion and stress tolerance (Khanjani *et al.,* 2024; Soltani *et al.,* 2019; Hai, 2015). Prebiotics like inulin, fructooligosaccharides (FOS), and mannan oligosaccharides (MOS) are non-digestible food ingredients, supplemented at 0.1–0.5% to stimulate beneficial gut bacteria growth and synergistically improve gut health, nutrient absorption and immune responses. Studies suggest that prebiotics in aquaculture feed can improve nutrient assimilation, disease resistance, and stress tolerance (Li *et al.,* 2024; Guerreiro *et al.,* 2018). The latest research studies suggest inulin and mushroom-based substances as novel prebiotics in aquafeeds (Patil *et al.,* 2024). Hoseinfar et al. (2016) reported that the dietary inclusion of fructooligosaccharide improved growth performance, survival, digestive enzyme activity and intestinal microbiota in common carp.

• Herbal extracts: Phytogenics, the compounds derived from herbs, spices, and other plant extracts, are increasingly utilized as natural growth promoters and immunostimulants in aquaculture feed. Extracts from medicinal plants like echinacea, turmeric and ginseng contain bioactive compounds with antimicrobial, anti-inflammatory and antioxidant properties that can enhance digestion and immune function, protect against oxidative stress, and promote infection recovery (Rana *et al.,* 2024). These plant-derived extracts offer a sustainable, residue-free alternative to traditional antibiotics and synthetic growth

promoters. For example, incorporating garlic extracts into fish diets has enhanced growth and immunity (Valenzuela-Gutiérrez *et al.,* 2021). Polyphenols and flavonoids (e.g., green tea, grape seed extracts), saponins, and alkaloids (e.g., quillaja, yucca extracts) are typically included at 0.01–1% in aquafeeds depending on species tolerance and bioavailability (Kazempoor *et al.,* 2022; Shehata et al., 2022).

• Essential oils: Plant-based essential oils derived from plants like oregano, thyme, garlic, citrus, ginger, cinnamon and rosemary are rich in bioactive compounds that exhibit antimicrobial and anti-inflammatory properties (El-Hack *et al.,* 2020; Souza *et al.,* 2019). These compounds are being explored as natural additives in feed to support gut health and immune function. Recent studies indicated that essential oils can improve feed conversion ratios and modulate gut microbiota, reducing pathogenic bacteria and enhancing beneficial species (Liang *et al.,* 2022). Single-cell oils produced by microorganisms are rich in essential fatty acids and serve as alternatives to fish oil. Goncalves *et al.* (2019) demonstrated that a phytogenic mix (a blend of anise, citrus, and oregano essential oils at 0.02%) in low-FM diets did not compromise growth performance, nutrient utilization, and health.

• Exogenous enzymes: Enzymes like proteases, amylases, and cellulases at 0.05–0.5% can act as catalysts that help digest plant-based feed ingredients, enhancing nutrient availability and digestibility and reducing feed costs. Phytases can reduce anti-nutritional factors like phytic acid, increasing mineral bioavailability. Glucose oxidase boosts immunity by reducing oxidative stress, and Lysozyme provides antimicrobial benefits (Liang *et al.,* 2022). Multi-carbohydrase blends are the latest innovation involving complexes combining cellulases, xylanases, and beta-glucanases to enhance fiber digestion in plant-based diets.

• Organic acids: Organic acids, including formic acid, citric acid, fumaric acid, propionic acid, butyric acid and lactic acid, are known to reduce gut pH, improve nutrient absorption, and promote beneficial gut microbiota when included at 0.05–0.3% (Rasidi *et al.,* 2024). These act as natural acidifiers, improving feed conversion ratios and reducing reliance on antibiotics. Compounds like formic acid and propionic acid improve feed digestibility and act as antimicrobial agents. Their inclusion in feed can reduce pathogen load and enhance feed efficiency (Niu *et al.,* 2023). The dietary supplementation of organic acids blended in rainbow trout helped partially replace fish meals with plant protein sources (Chen *et al.,* 2018). Research indicates that these acids can improve growth rates and act as non-antibiotic growth promoters, especially in young animals with underdeveloped digestive systems (Dibner and Buttin, 2022).

• Algal products: Algae, rich in essential fatty acids, vitamins, minerals and antioxidants, have been used to enhance pigmentation and immunity in fish. Astaxanthin, a carotenoid from microalgae, improves colouration and stress resistance. These algae-based products can be used as sustainable feed additives. DHA-rich algal oils are alternative sources of omega-3 fatty acids that can be crucial for fish health and growth. Single-cell ingredients (SCI) such as algal oils derived from *Schizochytrium* and *Crypthecodinium sp*. were included at 1–5% as a sustainable alternative to fish oil for omega-3 enrichment. Microalgae-derived pigments (e.g., astaxanthin from *Haematococcus pluvialis*) at 0.01–0.1% improve colouration and antioxidant activity, particularly in shrimp and salmon diets.

• Immunostimulants: Immunostimulants are added to aquafeed to boost the immune responses, reducing the infection risks and enhancing resilience to stressors. Antimicrobial compounds such as oxytetracycline and florfenicol can also be used for immunostimulation in fish, but under proper technical guidance. If overused, these may accumulate in fish bodies and can cause antimicrobial resistance. Hence, natural plant-derived immunostimulants were much preferred. Non-conventional immunostimulants include beta-glucans, marine polysaccharides, and herbal extracts. For example, beta-glucans are commonly derived from fungi and yeast cell walls. They have been extensively studied at 0.05–0.2% dietary inclusion levels for their immune-boosting properties (Devi *et al.,* 2023). Nucleotides were also used at 0.05–0.3% to support immune cell proliferation. They enhance macrophage and lymphocyte activity, improving disease resistance in aquaculture species (Li *et al.,* 2024).

• Metabolic modifiers: Metabolic modifiers are compounds that influence metabolic processes to optimize

growth, improve feed efficiency, and enhance energy utilization. Non-conventional metabolic modifiers include organic acids, amino acid analogues, and prebiotics (Hafeez *et al.,* 2024). Beta-glucans at 0.1–0.3% dietary inclusion enhance the fish's immune responses and improve disease resistance. Carnitine facilitates fat metabolism, providing energy and improving growth performance. In contrast, Choline chloride supports lipid metabolism and prevents fatty liver syndrome. Conjugated linoleic acid (CLA) promotes lean muscle growth and reduces fat deposition. Synbiotics modulate gut microbiota, improving nutrient absorption and metabolic efficiency (Varangia and Yadav, 2023). Chitosan and fucoidan are derived from crustaceans and brown algae, respectively. These polysaccharides exhibit high metabolic and immunostimulatory effects, enhancing growth and disease resistance in aquatic animals. Marine-derived polysaccharides, such as alginates and carrageenan, are also promising immunostimulants with additional antiviral and antioxidant effects (Vijayaram *et al.,* 2022).

• Mycotoxin binders: Mycotoxins are fungal-derived toxic metabolites that often contaminate the nutrient-rich aquafeeds. Due to the high risk of contamination, using mycotoxin binders in aquafeeds is a necessary strategy. A mycotoxin binder is a non-nutritional compound added to aquafeed to trap and immobilize the mycotoxin-binding agents or adsorbents in the fish gut, reducing their bioavailability. Various materials like clay, zeolitic, aluminium silicates, chabazite and stilbite can be used for this purpose (Hossain *et al.,* 2024). Paritova *et al.* (2013) reported that dietary inclusion of chankanay zeolites at 4% showed no adverse effects in the rainbow trout.

• Attractants: Attractants improve feed palatability and encourage higher feed intake, which is particularly valuable in aquaculture, where feed waste is a concern. Non-conventional attractants include yeasts, fermented plant extracts, and amino acid derivatives. Yeast products, such as those derived from Saccharomyces cerevisiae, have been shown to enhance feed intake and digestion in aquaculture species. They are rich in nucleotides, essential for growth and immune function (Zhou *et al.,* 2021). Studies have demonstrated that yeast-based attractants can significantly improve fish's growth performance and feed conversion efficiency (Cai *et al.,* 2025). Plant-based extracts, including garlic and ginger, offer natural attractant properties due to their aroma and taste, increasing feed intake (Kawamura *et al.,* 2019). These plant-derived attractants can also provide secondary benefits, such as antimicrobial and antioxidant properties, which support animal health. Synthetic compounds like DMPT (Dimethyl Propiothetin) can also enhance feed palatability and intake.

• Food colourants: They are added to fish feed to stimulate feed ingestion by improving feed visibility for fish or imparting a desired colouration within the carcass of the cultured fish (Varangia and Yadav, 2023). Carotenoid supplementation, including astaxanthin and canthaxanthin, was often used in ornamental fish feeds.

Role of additives in cost-effective feeding management

Integrating novel aquafeed additives has significant economic implications for the aquaculture industry, primarily through improved feed efficiency, reduced disease outbreaks, and enhanced growth performance (Panteli *et al.,* 2025). By optimizing nutrient absorption and gut health, additives such as enzymes, probiotics, organic acids, and functional proteins reduce the feed conversion ratio (FCR), producing more biomass per unit of feed input. This directly lowers feed costs that constitute 60–70% of total production expenses. Additionally, additives that enhance immunity and stress resistance minimize antibiotic dependency and decrease mortality rates, further reducing financial losses. Using natural and sustainable ingredients, such as plant-based proteins or microalgae, also contributes to long-term economic resilience by mitigating risks associated with volatile fishmeal and fish oil prices (Onomu and Okuthe, 2024). Although the initial cost of incorporating additives can be high, the long-term return on investment is often favourable due to better animal performance, higher market value of healthier stock, and reduced environmental impact fines or compliance costs (Marimuthu *et al.,* 2022). Therefore, the strategic inclusion of novel additives is economically viable and supports sustainable aquaculture development.

The integration of novel additives can lead to:

• Reduced feed costs

Table: List of a few commercially available aquafeed additives

S. No.	Product name	Company name	Key ingredients	Target species	Uses and benefits
1	ArgoRid®	Godrej Agrovet	Nutraceutical	Fish	Helps to manage fish lice infestations (Argulus Spot) and also aids in wound healing
2	AquaTe®	Alltech	Yeast-based prebiotics	Fish, shrimp	Supports gut health and improves resistance to pathogens.
3	AquaCare®	Evonik	Amino acid premix	Fish, shrimp	Provides nutritional balance and supports optimal growth and health.
4	AquaGuard®	Novus International	Organic acids	Fish, shrimp	Enhances pathogen control and gut health, improving feed efficiency and performance.
5	Aquagest®	Kemin Industries	Digestive enzymes	Fish, shrimp	Enhances nutrient digestion, leading to better feed utilization and growth.
6	Aqualyso®	Olmix Group	Algae-based compounds	Fish, shrimp	Reduces stress and improves resilience and overall growth.
7	AquaMax®	Cargill	Balanced nutrients, additives	Fish	provides balanced nutrition to optimize growth and health.
8	AquaSafe®	Adisseo	Antioxidants	Fish, shrimp	Reduces oxidative stress, supports health, and extends feed shelf-life.
9	AquaStar®	Biomin	Multi-strain probiotics	Shrimp	Improves gut health and disease resistance, increasing survival and growth.
10	AquaVit®	DSM Nutritional Products	Vitamins, minerals	Fish, shrimp	Prevents nutritional deficiencies and supports optimal health and development.
11	Digestarom®	Biomin	Phytogenic compounds	Fish, shrimp	Enhances feed palatability and intake while supporting digestive function.
12	Microvit®	Adisseo	Essential vitamins	Various aquaculture species	Provides essential vitamins to ensure optimal health and growth.
13	Mycofix®	Biomin	Mycotoxin-deactivating enzymes, adsorbents	Fish, shrimp	Manages mycotoxin risks, enhancing feed safety and animal health.
14	Rhodimet® AT88	Adisseo	Hydroxy methionine	Fish, shrimp	Supplies essential methionine, promoting protein synthesis, growth, and efficiency.
15	Selisseo®	Adisseo	Organic selenium	Various aquaculture species	Supports antioxidant defence and boosts immunity and overall health.

• Species-specific responses

• Enhanced growth rates

• Lower disease management costs

• Sustainability

Challenges and future perspectives

While the benefits are significant, several challenges still persist. The cost of Additives can be a significant problem, as some novel additives can be expensive due to their manufacturing processes, R&D, and availability, potentially offsetting savings from improved efficiency. The hurdles from the concerned regulatory bodies, such as FSSAI, CAA, etc., might also delay commercial production and market availability (Zhu *et al.,* 2016). Approval processes from these bodies for the new additives can be lengthy and complex. These high costs and limited access can hinder the adoption process among small-scale farmers, especially in developing regions. Apart from the regulatory approvals and consumer acceptance, potential environmental impacts persist. Hence, future research should focus on long-term effects, optimal dosages, and synergistic combinations of additives to maximize benefits and minimize any adverse environmental effects.

Conclusion

Novel feed additives can revolutionize aquaculture by enhancing feed efficiency, promoting health, and reducing costs at a more marginal scale. Advancements in biotechnology and a better understanding of fish physiology are paving the way for more effective and affordable feed additives. Emphasis on sustainability and environmental impact will continue to drive innovation in this field. Their strategic incorporation into feeding regimes is pivotal, and they present a promising avenue for enhancing the efficiency and sustainability of aquaculture operations. These additives can be crucial in cost-effective feed and feeding management by improving growth performance, health status, and feed utilization. However, careful consideration of economic, regulatory, and species-specific factors is essential for their successful integration into aquaculture practices.

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