Nutraceuticals in aquaculture: a natural approach to fish health management

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Abstract

Aquaculture is one of the fastest-growing food production sectors and plays a crucial role in global food, livelihood and nutritional security. However, the intensification of aquaculture practices has increased the incidence of disease outbreaks, environmental stress, and dependence on antibiotics, leading to concerns regarding antimicrobial resistance, environmental contamination, and residue accumulation in aquatic products. Nutraceuticals have emerged as promising natural alternatives for sustainable fish health management. These bioactive compounds, including probiotics, prebiotics, amino acids, fatty acids, vitamins, seaweed extracts, herbal products, and nano-nutraceuticals, provide both nutritional and therapeutic benefits. Nutraceuticals enhance growth performance, improve feed utilization, strengthen immune responses, promote beneficial gut microbiota, and increase disease resistance in aquatic organisms. Their application also contributes to improved water quality and reduced environmental impacts. Despite challenges related to standardization, cost, and large-scale adoption, nutraceuticals offer significant potential for developing antibiotic-free, environmentally sustainable, and economically viable aquaculture systems in the future.

Introduction

Aquaculture is one of the fastest-growing food production sectors in the world and plays a vital role in global food and nutritional security. Increasing demand for fish protein, declining capture fisheries, rapid population growth, and changing dietary preferences have significantly enhanced the importance of aquaculture production worldwide (FAO 2024; Samanta et al., 2022). The intensification of aquaculture practices has also led to several challenges, including disease outbreaks, poor water quality, stress, reduced immunity, and increased susceptibility to infections in cultured fish and shellfish.

To control infectious diseases and improve production, antibiotics and chemicals have been increasingly used in aquaculture systems. However, indiscriminate and prolonged use of antibiotics has resulted in serious problems such as antimicrobial resistance, environmental contamination, destruction of beneficial microbial communities, and accumulation of drug residues in aquatic organisms and the surrounding environment (Cabello, 2006; Gutiérrez-

Pacheco et al., 2026). These concerns have increased the demand for safer, eco-friendly, and sustainable alternatives for fish health management.

In this context, nutraceuticals have emerged as promising natural alternatives for sustainable aquaculture. nutraceuticals are bioactive compounds derived from natural sources that provide both nutritional and therapeutic benefits (Shinde & Sukhdhane, 2023). With growing consumer awareness regarding food safety and environmental sustainability, the use of nutraceuticals in aquafeeds is rapidly increasing worldwide. Their application not only supports healthy fish production but also contributes to the development of environmentally sustainable and antibiotic-free aquaculture systems. Therefore, nutraceuticals are considered an important component of future fish health management strategies and sustainable aquaculture development.

What are nutraceuticals?

The term "nutraceutical" was coined by Stephen DeFelice in 1989 and refers to food or food-derived substances that provide health benefits beyond basic nutrition. Nutraceuticals include a wide range of compounds such as probiotics, prebiotics, vitamins, amino acids, fatty acids, seaweed extracts, herbal products, antioxidants, minerals, and enzymes as mentioned below in the table 1.

Table 1. Major types of nutraceuticals used in aquaculture

Type of nutraceutical	Examples	Major functions
Probiotics	*Lactobacillus, Bacillus*	Improve gut health and immunity
Prebiotics	Mannan oligosaccharides	Promote beneficial gut microbes
Amino acids	Arginine, Lysine	Growth and immune enhancement
Vitamins	Vitamin C, Vitamin E	Antioxidant activity
Fatty acids	Omega-3 PUFA	Improve growth and immunity
Seaweed extracts	Fucoidan, Ulvan	Immunostimulation
Herbal products	Garlic, Turmeric	Antimicrobial and antioxidant effects
Nanonutraceuticals	Nano-selenium	Improved nutrient delivery
Reference: Shinde & Sukhdhane, 2023; Samanta et al., 2022		

Importance of nutraceuticals in aquaculture

Nutraceuticals are gaining significant importance in aquaculture due to their ability to reduce stress, improve fish health and productivity through natural and eco-friendly approaches without causing harmful environmental effects (Varghese et al., 2021). The major benefits of the nutraceuticals in aquaculture are depicted in the Fig. 1

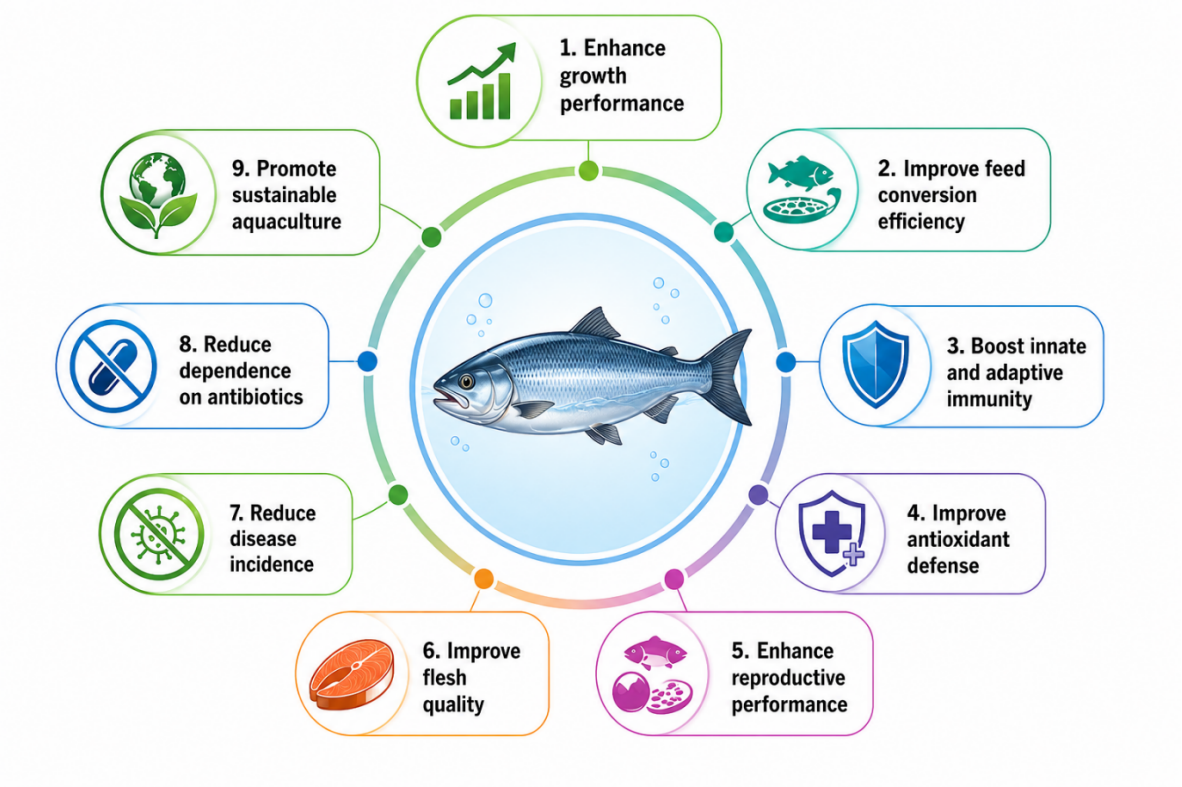

Fig 1: Depicting the major benefits of nutraceuticals in aquaculture

Probiotics as nutraceuticals in aquaculture

Probiotics are live microorganisms which, when administered in adequate amounts, confer health benefits to the host by improving microbial balance and enhancing disease resistance. In aquaculture, probiotics are increasingly used as eco-friendly alternatives to antibiotics for maintaining fish health and improving production efficiency. According to the widely accepted definition proposed by Fuller R. (1989), probiotics are "live microbial feed supplements which beneficially affect the host animal by improving its intestinal microbial balance." Common probiotic bacteria used in aquaculture include species of *Lactobacillus*, *Bacillus*, and *Enterococcus*, which are known for their ability to colonize the gastrointestinal tract and produce beneficial metabolites (Hoseinifar et al., 2024).

Probiotics play a crucial role in improving digestion and nutrient absorption by secreting digestive enzymes and enhancing gut microflora composition. They stimulate both innate and adaptive immune responses, thereby increasing the resistance of fish against pathogenic microorganisms. Probiotics also inhibit the growth of harmful bacteria through competitive exclusion and the production of antimicrobial compounds such as bacteriocins, organic acids, and hydrogen peroxide. In addition, their application contributes to improved water quality by reducing organic waste accumulation and harmful metabolites in culture systems. As a result,

probiotics help reduce disease incidence, improve survival rate, and enhance overall growth performance in fish and shellfish culture systems (Verschuere et al., 2000; Kesarcodi-Watson et al., 2008).

Prebiotics as nutraceuticals in aquaculture

Prebiotics are non-digestible feed ingredients that selectively stimulate the growth and activity of beneficial microorganisms in the gastrointestinal tract, thereby improving host health. In aquaculture, prebiotics are widely used as functional feed additives to enhance intestinal health, immunity, and growth performance in fish and shellfish. According to Gibson G.R. and Roberfroid M.B. (1995), prebiotics are defined as "non-digestible food ingredients that beneficially affect the host by selectively stimulating the growth and/or activity of one or a limited number of bacteria in the colon." Commonly used prebiotics in aquaculture include mannan oligosaccharides (MOS), fructooligosaccharides (FOS), and inulin. Prebiotics stimulate non-specific immune responses, thereby increasing resistance against bacterial and viral infections. Another important role of prebiotics is their synergistic interaction with probiotics, where they serve as substrates for beneficial microbes and enhance probiotic colonization and activity in the digestive tract. Due to these beneficial effects, prebiotics are considered promising alternatives to antibiotic growth promoters and contribute significantly to sustainable aquaculture practices (Ringø et al., 2010; Dimitroglou et al., 2009).

Amino acids and fatty acids as nutraceuticals

Essential amino acids (EAA) and fatty acids are important nutraceuticals in aquaculture because they play vital roles in fish growth, metabolism, immunity, and overall health. EAA such as arginine and lysine improve protein synthesis, feed utilization, growth performance, and immune function in fish (Wu, 2009).

Polyunsaturated fatty acids (PUFAs), particularly omega-3 fatty acids such as EPA and DHA, are also important functional nutrients in aquaculture. Omega-3 fatty acids improve growth and survival, enhance immune response, support brain and tissue development, and improve reproductive performance in fish (Tocher, 2010). Seaweeds, microalgae, and marine oils are major natural sources of omega-3 fatty acids used in aquafeeds. The inclusion of amino acids and omega-3 fatty acids in fish diets helps improve fish health and productivity.

Vitamins and Antioxidants

Vitamins are essential micronutrients required for normal growth, metabolism, reproduction, and immune function in fish (Table 2). They play important roles in maintaining physiological

balance and improving resistance against environmental stress and diseases. Among them, vitamin C and vitamin E are important antioxidants widely used as nutraceuticals in aquaculture. Vitamin C enhances immune response, collagen synthesis, wound healing, and disease resistance, while vitamin E protects cell membranes from oxidative damage caused by free radicals (Jobling, 2012).

Table 2. Important Vitamins and Their Functions

Vitamin	**Major function in fish**
Vitamin A	Growth, vision, epithelial tissue development
Vitamin D	Bone formation and calcium-phosphorus metabolism
Vitamin E	Antioxidant protection against oxidative stress
Vitamin K	Blood clotting and bone metabolism
Vitamin C	Immunity enhancement and antioxidant activity
Vitamin B1 (Thiamine)	Carbohydrate metabolism and nerve function
Vitamin B2 (Riboflavin)	Energy metabolism and enzyme activity
Vitamin B3 (Niacin)	Protein and lipid metabolism
Vitamin B5 (Pantothenic acid)	Coenzyme synthesis and metabolism
Vitamin B6 (Pyridoxine)	Amino acid metabolism and immunity
Vitamin B7 (Biotin)	Fatty acid synthesis and metabolism
Vitamin B9 (Folic acid)	DNA synthesis and blood cell formation
Vitamin B12 (Cobalamin)	Red blood cell formation and growth
Reference: Jobling, 2012; Khanjani et al., 2025.	

Seaweed-based nutraceuticals

Seaweeds are emerging as important nutraceutical sources in aquaculture because they contain a wide range of bioactive compounds such as polysaccharides, vitamins, minerals, polyphenols, pigments, and omega-3 fatty acids. These compounds improve fish growth, immunity, antioxidant defense, and disease resistance. Brown seaweeds such as *Laminaria* and *Ascophyllum*, red seaweeds such as *Gracilaria* and *Porphyra*, and green seaweeds such as *Ulva* are commonly incorporated into aquafeeds because of their functional and therapeutic properties (Selvam et al., 2024; Li et al., 2023; Samsudin et al., 2020).

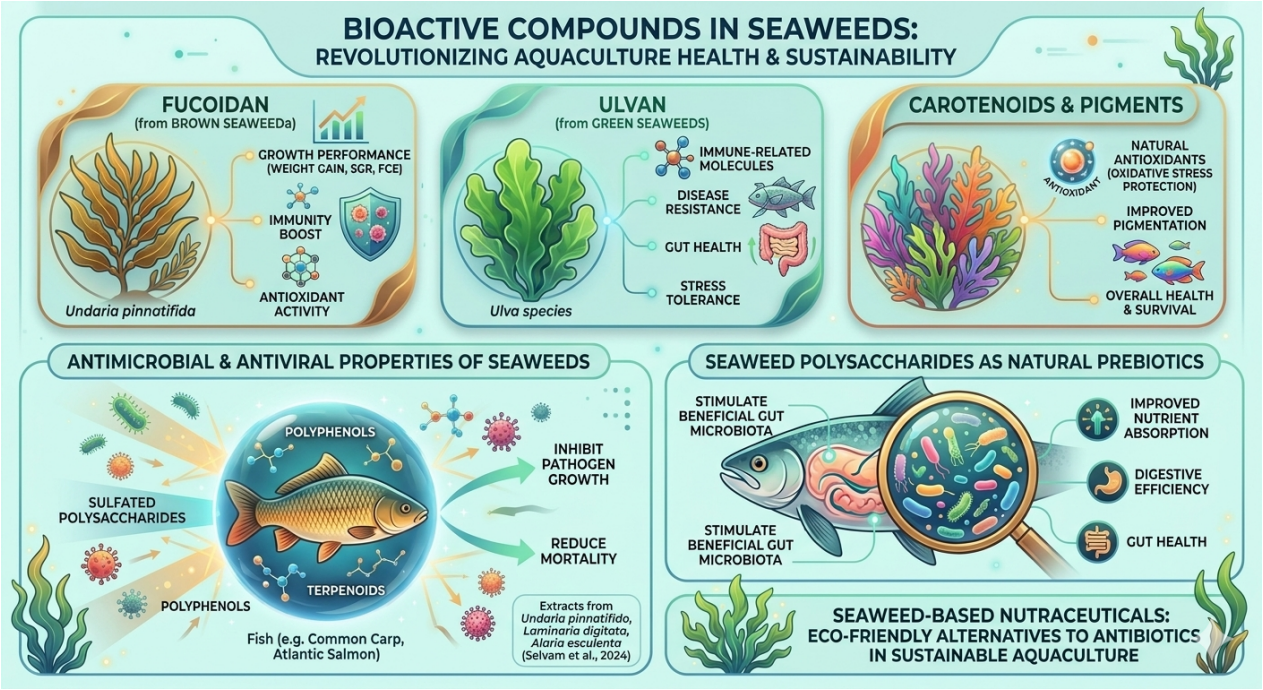

Fig. 2. Pictorial representation illustrating the role of seaweed-based nutraceuticals in maintaining fish health through enhancement of immunity, antioxidant defense, gut health, disease resistance, and growth performance in aquaculture species.

Nano-nutraceuticals in aquaculture

Nanotechnology has introduced innovative strategies for improving nutrient delivery, disease management, and fish health in aquaculture. Nanonutraceuticals are nano-sized nutritional or bioactive compounds designed to enhance nutrient utilization and biological efficiency in aquatic organisms. Due to their small particle size, nano-nutraceuticals possess high bioavailability, improved absorption efficiency, enhanced stability, and controlled release properties, making them highly effective in aquafeed applications. Common nano-nutraceuticals used in aquaculture include nano-selenium, which enhances antioxidant activity and immunity; iron nanoparticles, which improve growth and metabolic functions; chitosan nanoparticles, which are widely used for drug and nutrient delivery; and nano-vaccines, which help in disease prevention and immune stimulation. Among these, nano-selenium supplementation has shown significant improvement in antioxidant status, growth performance, and disease resistance in fish species such as carp and sturgeon (Samanta et al., 2022).

Advantages of nutraceuticals over antibiotics in aquaculture

The extensive use of antibiotics in aquaculture has raised serious concerns regarding antimicrobial resistance, environmental contamination, and residue accumulation in aquatic products. In contrast, nutraceuticals offer a natural and eco-friendly alternative for improving

fish health, immunity, and disease resistance (Table 3). Nutraceuticals such as probiotics, prebiotics, seaweed extracts, vitamins, and bioactive compounds enhance the innate immune system and improve overall fish performance without causing harmful environmental effects. Therefore, nutraceutical-based health management strategies are considered more sustainable and safer for modern aquaculture systems (Ringø et al., 2010; Dawood et al., 2018).

Table 3. Comparison between antibiotics and nutraceuticals in aquaculture

Parameter	Antibiotics	Nutraceuticals	Reference
Nature	Synthetic or chemically derived compounds	Natural bioactive substances	Ringø et al. (2010)
Environmental impact	High; may contaminate water and sediments	Low and eco-friendly	Dawood et al. (2018)
Antibiotic resistance	Promotes antimicrobial resistance	Does not induce resistance	Cabello (2006)
Residue accumulation	Possible accumulation in fish tissues	Minimal or negligible residues	FAO (2019)
Immune enhancement	Limited immune stimulation	Strong immunomodulatory effects	Hoseinifar et al. (2018)
Effect on gut microbiota	May disrupt beneficial gut microbes	Supports beneficial gut microbiota	Ringø et al. (2010)
Disease prevention	Temporary disease control	Long-term health improvement	Dawood et al. (2018)
Sustainability	Lower sustainability	Highly sustainable approach	FAO (2019)
Consumer safety	Potential health concerns due to residues	Safer for consumers	Cabello (2006)
Application in aquaculture	Mainly therapeutic	Preventive and health-promoting	Hoseinifar et al. (2018)

Nutraceuticals are increasingly preferred in aquaculture because they improve fish health naturally while minimizing environmental risks and reducing dependence on antibiotics. Their ability to enhance immunity, support beneficial gut microbiota, and reduce antimicrobial resistance makes them highly suitable for sustainable aquaculture development.

Challenges in nutraceutical application

Despite their numerous advantages, the application of nutraceuticals in commercial aquaculture still faces several challenges. One of the major limitations is the lack of standardized dosage and feeding protocols for different fish species and culture conditions. The effectiveness of nutraceuticals often varies among species due to differences in metabolism, physiology, and environmental factors. In addition, some nutraceutical formulations are expensive, limiting their large-scale adoption in commercial farming systems. Limited awareness and technical knowledge among farmers regarding the proper use of nutraceuticals

also restrict their widespread application. Furthermore, long-term field validation studies are still needed to evaluate their efficacy, safety, and economic feasibility under diverse aquaculture conditions (Dawood et al., 2018). Therefore, further research is essential to optimize nutraceutical formulations and develop cost-effective strategies for sustainable aquaculture.

Future prospects

The future of nutraceuticals in aquaculture is highly promising because of the increasing global demand for antibiotic-free, healthy, and environmentally sustainable fish production. Advances in biotechnology, nutrition, and nanotechnology are expected to enhance the development of next-generation nutraceuticals for aquatic animals. Future research should focus on the development of species-specific nutraceutical formulations, integration of nanotechnology for targeted nutrient delivery, discovery of novel marine bioactive compounds, and production of functional aquafeeds for disease prevention and stress management. Precision nutrition approaches combining genomics, metabolomics, and microbiome studies may further improve the efficiency and application of nutraceuticals in fish health management (Hoseinifar et al., 2018).

Conclusion

Nutraceuticals have emerged as eco-friendly and sustainable alternatives for fish health management in modern aquaculture. They improve immunity, growth performance, antioxidant defense, feed utilization, gut health, and disease resistance while reducing dependence on antibiotics and synthetic chemicals. Nutraceuticals such as probiotics, prebiotics, seaweed-derived compounds, vitamins, amino acids, fatty acids, and nano-nutraceuticals have shown significant potential in improving fish health and aquaculture productivity. Continued research, technological advancements, and farmer awareness programs will further strengthen the role of nutraceuticals in sustainable aquaculture production and aquatic animal health management.

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