



BIOGENIC DIETARY PROMOTERS IN AQUACULTURE: NATURE-BASED SOLUTIONS FOR ENHANCING GROWTH, HEALTH, AND SUSTAINABILITY – A REVIEW

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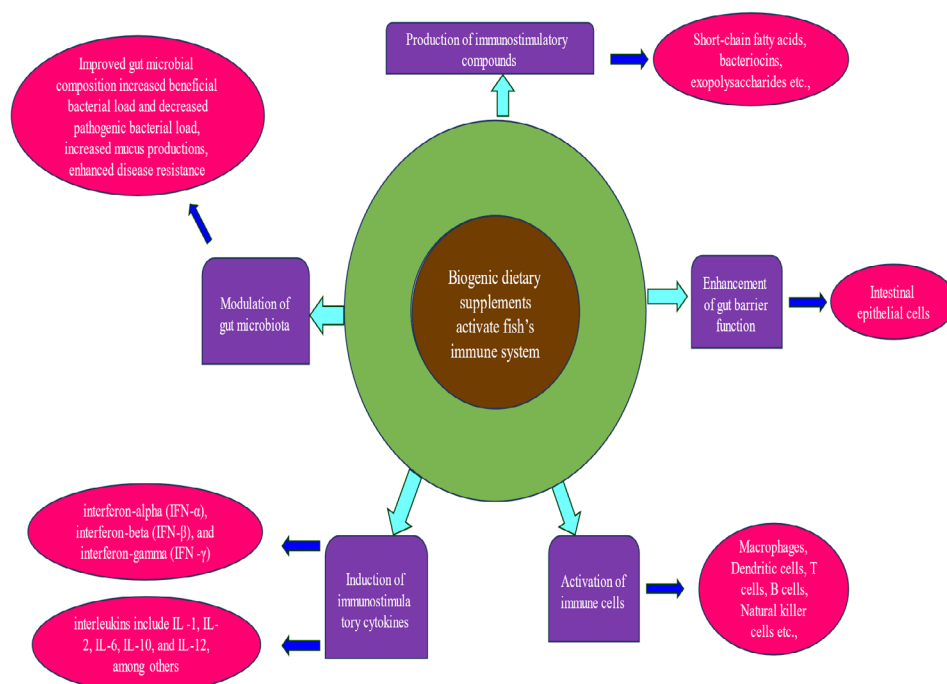
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Abstract

Aquaculture, as a rapidly expanding global industry, is increasingly challenged by both infectious and non-infectious diseases, posing significant threats to fish health and production. Traditional interventions, such as antibiotics and vaccines, though effective, raise concerns regarding environmental impact and the potential for resistance development. This review explores the promising role of dietary biogenic promoter supplements as an innovative, sustainable alternative for aquaculture. By analyzing emerging literature, we highlight the significance of these nature-based solutions, which offer cost-effective, non-toxic, and eco-friendly options to enhance aquaculture productivity. Biogenic supplements, derived from herbs, beneficial microbes, insects, nutrients, bioactive molecules, and nanoparticles, have shown potential in improving feed quality, promoting growth, boosting disease resistance, enhancing immune system function, and supporting overall health in aquatic species. This comprehensive review demonstrates the efficacy of biogenic-mediated supplements in fostering aquaculture sustainability by minimizing the need for traditional chemical interventions. Furthermore, the analysis identifies critical research gaps, particularly in determining optimal supplement concentrations and their species-specific effects. Additionally, large-scale field trials are recommended to validate laboratory findings and assess their practical applications in real-world settings. By synthesizing current research, this review provides valuable insights into the future trajectory of aquaculture practices, positioning biogenic dietary supplements as key contributors to sustainable and efficient aquaculture development.

Key words: aquaculture, algae, bioactive molecules, herbs, probiotics, nutrients, nanoparticles



The projected increase in the global population to 9.7 billion by 2050, coupled with a corresponding rise in food demand by 60–100%, presents substantial challenges for food production, agriculture, and environmental sustainability (Yarnold et al., 2019). As population growth accelerates, the need for nutrient-rich protein sources becomes increasingly urgent, with aquaculture emerging as a critical sector to address this demand (Sattanathan et al., 2020 a, b). Aquaculture, or aquafarming, plays a pivotal role in global food production, contributing significantly to human nutrition by providing a steady supply of fish and other aquatic products (Prem and Tewari, 2020). The anticipated expansion of the global animal feed market, projected to reach around 110.29 billion USD by 2025 at a 4% annual growth rate, reflects the growing demand for protein-rich meat and animal-derived products (Technavio, 2021). This market growth is driven by the increasing needs of both livestock and aquaculture industries, which are key players in addressing the protein requirements of a burgeoning global population. Moreover, advancements in animal nutrition and feed technology are enhancing feed production efficiency, further supporting the growth of these sectors. Dietary supplementation is widely adopted in aquaculture to enhance various aspects of fish farming, including improving feed efficiency, promoting growth, and bolstering non-specific immune system responses. A range of supplements, including vitamins, minerals, amino acids, probiotics, prebiotics, and enzymes, are incorporated into fish diets to ensure nutritional balance and optimize health outcomes (Abdel-Tawwab, 2016; Hoseini et al., 2017, 2018). Sustainable practices in agriculture and aquaculture are essential for overcoming challenges posed by emerging diseases, climate change, and socio-economic pressures while maintaining food security (Calicioglu et al., 2019). Disease outbreaks represent a major concern in aquaculture, as they can lead to significant economic losses and threaten the sector's sustainability. Diseases in aquaculture can be categorized into communicable and non-communicable types. Communicable diseases, caused by pathogens such as bacteria (e.g., *Aeromonas hydrophila*, *Pseudomonas* spp., *Streptococcus* spp., and *Vibrio* spp.), fungi, viruses, parasites, and protozoa, pose a direct threat to fish health. Non-communicable diseases, on the other hand, often result from factors like poor water quality, pollution, and malnutrition (El-Sayed Ali et al., 2014, 2018; Idowu et al., 2017). Biogenic nutritional supplements offer a promising solution to these challenges, playing a crucial role in enhancing growth, improving disease resistance, strengthening immune function, and promoting the overall well-being of aquatic species (Vijayaram et al., 2024 a, b, c, d, e, 2023 a, b, 2022). These supplements, classified by their origin – whether animal-derived, plant-derived, or microbial-derived – or by their function as vitamins, minerals, enzymes, antioxidants, and others, are gaining attention as natural alternatives to synthetic feed additives. Biogenic supplements not only support the growth and productivity of aqua-

culture species but also contribute to the sustainability of the aquatic ecosystem. They do so by optimizing nutrient recycling, minimizing waste, and promoting efficient use of resources during feed consumption and reproduction (Dawson et al., 2018). In intensive aquaculture, approximately 16% of wild-caught fish species are used as feed, which raises concerns about overfishing and its effects on marine ecosystems (Dineshababu et al., 2019). Feed conversion ratios further underscore the resource efficiency of aquaculture compared to other livestock systems. For example, producing 1 kg of edible meat requires approximately 1.4–1.8 kg of feed for poultry, 2.6–4.4 kg for pork, 3.5–9 kg for beef, and only 1.1–1.6 kg for seafood, making aquaculture one of the most efficient methods of protein production (Jones et al., 2020). Thus, biogenic dietary supplements not only address the nutritional needs of aquaculture species but also offer a sustainable path forward for meeting global protein demands while minimizing environmental impact.

Biogenic products and medicinal herbs in aquaculture

Biogenic products such as probiotics, antimicrobial peptides, prebiotics, Chinese herbs, and medical nutritional factors are increasingly utilized in aquaculture to bolster the immune systems of aquatic animals and combat diseases (Mohan et al., 2019). These products play a crucial role in enhancing the overall health and disease resistance of fish and other aquatic organisms.

Biogenic immunostimulators

Various biogenic immunostimulators, including seaweed, probiotics, and beneficial fungi, have gained recognition for their antimicrobial properties and their capacity to enhance the immune system and feed quality in aquaculture (Efianda et al., 2018; Ramadhani et al., 2019; Rudi et al., 2019).

Medicinal herbs

The utilization of medicinal herbs and traditional remedies in animal husbandry dates back to ancient times, serving to promote animal health, treat diseases, and enhance overall well-being. In recent decades, there has been a resurgence of interest in employing medicinal herbs and traditional remedies within the aquatic division, particularly in aquaculture (Das et al., 2018; Vijayaram et al., 2023 a, b). Different kinds of herbal dietary supplements have shown significant efficacy in improving immune system activity across diverse fish species: rosemary (*Rosmarinus officinalis*) leaf and ginger (*Zingiber officinale*) for common carp (*Cyprinus carpio*) (Yousefi et al., 2019; Mohammadi et al., 2020 a, b); garlic (*Allium sativum*), wood betony (*Stachys lavandulifolia*), and kesum (*Polygonum minus*) leaf for rainbow trout (*Oncorhynchus mykiss*) (Esmaeili et al., 2017; Moghanlou et al., 2018; Adel et al., 2020; Ghafarifarsani et al., 2022); purple coneflower (*Echinacea purpurea*), thyme (*Thymus vulgaris*) essential oil, and Mexican daisy

(*Tridax procumbens*) for Nile tilapia (*Oreochromis niloticus*) (Abdel-Rahman et al., 2018; Valladão et al., 2019; Adeshina et al., 2021); common mallow (*Malvae sylvestris*) for rainbow trout (*Oncorhynchus mykiss*) fingerlings and *Mentha piperita* for Siberian sturgeon (*Acipenser baerii*) (Rashidian et al., 2020; Adel et al., 2024; Ghafari-farsani et al., 2021 a); lavender (*Lavandula angustifolia*) for goldfish (*Carassius auratus*) (Pastaki et al., 2023). Table 1 provides a summary of these medicinal herbs and their effects.

Microalgae in aquaculture

Microalgae represent a promising and sustainable feed ingredient for aquaculture, offering various benefits such as improved feed intake, growth performance, and overall health. As the aquaculture sector continues to expand and address sustainability challenges, microalgae-based feeds are positioned to play a significant role in its future development (Kupchinsky et al., 2015; Table 2).

Nutritional value and safety

Numerous microalgae species, including *Arthrospira*, *Chlorella*, *Chaetoceros*, *Haematococcus*, *Isochrysis*, *Nannochloropsis*, *Pavlova*, *Phaeodactylum*, *Skeletonema*, *Tetraselmis*, and *Thalassiosira* are Generally Recognized as Safe (GRAS) and widely used in aquaculture due to their safety for both human and animal consumption. These microalgae species have a long history of safe

use and are renowned for their nutritional value and potential health benefits (Madeira et al., 2017).

Importance as nutrient sources

Microalgae and their by-products serve as valuable nutrient sources in aquaculture, particularly for zooplankton. As primary producers in aquatic ecosystems, microalgae provide essential nutrients and energy at the base of the food chain. Zooplankton, including various copepods, rotifers, and other small organisms, rely on microalgae as a primary food source (Tibaldi et al., 2015).

Protein and amino acid profiles

Microalgal biomass is recognized for its rich protein and amino acid profiles, making it an excellent source of high-quality protein for aquaculture and animal feed production. The protein content of microalgae differs depending on the species and cultivation conditions, but many microalgae species offer highly nutritious protein sources (Becker, 2007; Sarker et al., 2018; Carneiro et al., 2020).

Bioactive molecules

Microalgae contain various bioactive molecules such as proteins, lipids, carbohydrates, and pigments, which can have specific health and growth-promoting effects in aquaculture species. These components make microalgae valuable for formulating nutritious and health-promoting feeds for various aquatic animals (Apandi et al., 2019).

Table 1. Herbs used as a supplement for aquatic animals

Herbal's local name and scientific name	Aquatic animal's local name and scientific name	Administration/dosages	Response	Duration of treatment	References
Ginger (<i>Zingiber officinale</i>)	Grass carp (<i>Ctenopharyngodon idella</i>)	4 mg/l	Preventing <i>Ichthyophthirius multifiliis</i> infections	–	Fu et al. (2019)
Wood betony (<i>Stachys lavandulifolia</i>)	African cichlid (<i>Sciaenochromis fryeri</i>)	8%	Enhancing liver function and resilience to acute stress	10 weeks	Mohammadi et al. (2019)
Thyme (<i>Zataria multiflora</i>)	Rainbow trout (<i>Oncorhynchus mykiss</i>)	Oral, 0, 1, 2.5, and 5 g/kg of ginger extract	Increased weight gain (WG), feed conversion ratio (FCR), lymphocytes (Ly), alkaline phosphatase (ALP), and acid phosphatase (ACP)	Ethanollic ginger, 45 days	Mirghaed et al. (2020)
Garlic (<i>A. sativum</i>)	Catfish (<i>Heteroclarias</i>)	2.5%	Enhanced growth performance	–	Ayanwale et al. (2021)
Coriander (<i>Coriandrum sativum</i>)	Rainbow trout (<i>O. mykiss</i>)	Seed extract 2%	Enhanced hematocrit value, white blood cell count, hemoglobin content, and red blood cell count	8 weeks	Farsani et al. (2019)
Black cumin oil (<i>Nigella sativa</i>)	Rainbow trout (<i>O. mykiss</i>)	1%	Enhanced growth performance, body composition, and lipid profile	144 days	Öz et al. (2018)
Elephant's foot (<i>Elephantus scaber</i>)	Nile tilapia (<i>O. niloticus</i>)	5 g/kg	Enhanced disease resistance against <i>Streptococcus agalactiae</i> infections	8 weeks	Doan et al. (2019)

Table 2. The use of algae as a dietary feed supplement in aquaculture and their impact on aquatic animals

Algae	Algae (Family)	Aquatic organisms	Replaced ingredients	Dietary inclusion level (g/kg or %)	Beneficial effects	References
<i>Arthrospira platensis</i>	Microcoleaceae	Giant river prawn (<i>Macrobrachium</i>)	FM	50%	Improved growth performance and feed conversion efficiency	Radhakrishnan et al. (2016)
<i>Chlorella vulgaris</i>	Chlorellaceae	Carp (<i>Carassius auratus gibelio</i>)	FM	0.4–2.0%	Augmented immunoglobulin IgM and IgD levels, interleukin-22 (IL-22) expression, and chemokine (C-C motif) ligand 5 (CCL-5) production	Khani et al. (2017)
<i>Gracilaria fisheri</i>	Gracilariaceae	Giant tiger prawn (<i>P. monodon</i>)	FM	100–200 µg/ml	Improved immune system function and enhanced resistance against white spot syndrome virus	Wongprasert et al. (2014)
<i>Spirulina</i> sp.	Spirulinaceae	Common carp (<i>Cyprinus carpio</i>)	FM	5 g/kg	Increased growth rate and improved feed conversion ratio	Nandeesh et al. (1998)
<i>S. platensis</i>	Microcoleaceae	Silverfish (<i>Trachinotus ovatus</i>)	FM	5%	Enhanced composition and feed utilization	Lin et al. (2016)

Table 3. Commonly applied probiotic supplements used as feed additives for fish (Vijayaram et al., 2023 b)

Genus	Probiotics	Example of target fish species
<i>Bacillus</i>	<i>Bacillus coagulans</i>	<i>Cyprinus carpio</i> (common carp), <i>Scophthalmus maximus</i> (turbot)
	<i>Bacillus subtilis</i>	<i>O. niloticus</i> (Nile tilapia)
	<i>Bacillus licheniformis</i>	<i>Ctenopharyngodon idella</i> (grass carp)
	<i>Bacillus cereus</i>	<i>Heteropneustes fossilis</i> (catfish)
<i>Bifidobacterium</i>	<i>Bifidobacterium bifidus</i>	<i>Cyprinus rubrofasciatus</i> (koi fish)
<i>Carnobacterium</i>	<i>Carnobacterium divergens</i>	<i>Gadus morhua</i> (Atlantic cod)
<i>Enterococcus</i>	<i>Enterococcus faecium</i>	<i>O. niloticus</i> (Nile tilapia)
<i>Lactobacillus</i>	<i>Lactobacillus casei</i>	<i>Cyprinus carpio</i> (common carp)
	<i>L. plantarum</i>	<i>Acanthopagrus schlegelii</i> (Black Sea bream)
	<i>L. rhamnosus</i>	<i>O. niloticus</i> (Nile tilapia)
<i>Lactococcus</i>	<i>L. lactis</i>	<i>Siniperca chuatsi</i> (Mandarin fish)
<i>Pediococcus</i>	<i>Pediococcus acidilactici</i>	<i>Oncorhynchus mykiss</i> (rainbow trout)
<i>Streptomyces</i>	<i>Streptomyces</i> sp.	<i>Danio rerio</i> (zebrafish)
<i>Saccharomyces</i>	<i>Saccharomyces cerevisiae</i>	<i>Pangasianodon hypophthalmus</i> (striped catfish)
<i>Weissella</i>	<i>Weissella cibaria</i>	<i>Cyprinus carpio</i> (common carp)

Carotenoids and astaxanthin

Microalgae produce diverse carotenoids, including α -carotene, β -carotene, astaxanthin, lutein, and zeaxanthin, which are important antioxidants and pigments. Astaxanthin, in particular, is a valuable nutrient with numerous benefits for various aquatic animals, enhancing pigmentation, acting as an antioxidant, promoting growth, and improving immune and inflammatory responses (Lu et al., 2021).

Lipid content and functional properties

Microalgae, such as *Chlorella vulgaris* and *Bortryococcus braunii*, exhibit varying lipid yields, with implications for their functional properties. Additionally, microalgae pigments possess important biological functions such as antioxidants, anti-obesity agents, an-

ti-inflammatory agents, and neuroprotective properties (D'Alessandro and Filho, 2016).

Spirulina and *Dunaliella*

Certain microalgae strains, like *Spirulina* and *Dunaliella*, are particularly notable for their high protein content. *Spirulina*, for instance, contains 50–70% proteins, making it valuable for both human and animal nutrition. It is widely used in aquaculture to provide essential protein and nutrients to farmed fish and other aquatic species (Ejike et al., 2017).

Probiotics in aquaculture

Probiotics offer numerous benefits in aquaculture, spanning enhanced water quality, disease resistance,

growth rate, feed conversion ratio, and regulation of the immune system. They also positively impact the host, reducing reliance on broad-spectrum antibiotics (Lin et al., 2017; Vijayaram and Kannan, 2018; Mirbakhsh et al., 2023; Morshedi et al., 2021; Van Doan et al., 2020; Guardiola et al., 2016). Probiotic feed supplements have been shown to improve fish feed conversion, and growth, reduce mortality, and boost immune system responses, making them ideal for fish feeding (Kumar et al., 2016; Table 3).

Prebiotics, postbiotics, minerals and synbiotics in aquaculture

Different categories of organic and inorganic compounds, such as prebiotics, postbiotics, and minerals, serve as valuable feed additives in aquaculture, contributing to the health, well-being, and growth of aquatic species.

Prebiotics

Prebiotics, primarily composed of carbohydrates, especially oligosaccharides, polyphenols, and long-chain fatty acids, support the growth of host microorganisms (Gibson et al., 2017). These compounds, including fructooligosaccharides (FOS), chitosan, polyphenols, butyric acid, propionic acid, lentinan, lipoteichoic acid, fucoidan, and isoflavones, offer benefits such as enhancing the growth, immune system, survival, and disease resistance in aquatic species against pathogens. Prebiotics represent innovative feed additives in aquaculture, contributing to the overall health and performance of cultured organisms (Yang et al., 2020 a, b; Magrone et al., 2018; Vijayaram et al., 2022).

Postbiotics

Postbiotics are bioactive molecules or structural components derived from probiotics (Salminen et al., 2021). These compounds play a crucial role in supporting host health and performance. Postbiotics, derived from the fermentation processes of probiotics, offer similar benefits to prebiotics, contributing to growth promotion, immune system enhancement, and disease resistance in aquatic species.

Minerals

Minerals are essential components of aquafeeds, playing critical roles in regulating various physiological processes in fish. Magnesium, for example, is crucial for fish growth, particularly in controlling myotube formation and muscle cell proliferation (Maradze et al., 2019). Adequate mineral supplementation in aquafeeds ensures optimal growth, development, and overall health of cultured aquatic organisms.

Nutrient absorption and intestinal health

In addition to prebiotics, postbiotics, and minerals, certain feed additives containing fatty acids, essential amino acids, vitamins, and other nutrients are employed to enhance intestinal health and promote nutrient absorp-

tion through intestinal barriers (Martin and Król, 2017). Nutrients are absorbed in the intestinal region, where enzymes, microorganisms, and genes are regulated and activated. Studies utilizing microbiome and transcriptome tools provide insights into these processes (Martin et al., 2016; Dawood et al., 2020).

Benefits and sustainability

Bioactive molecules added to aquafeeds offer numerous benefits, including antimicrobial, immunostimulant, antioxidant, growth-promoting, and anti-inflammatory properties. These techniques are not only economically viable and environmentally sustainable but also devoid of adverse effects, contributing to the sustainability and efficiency of aquaculture operations (Wang et al., 2017; Ragunath and Ramasubramanian et al., 2022; Firmino et al., 2021).

Synbiotics

The utilization of synbiotics, a combination of probiotics and prebiotics, in aquaculture, presents a promising and relatively recent approach. Synbiotics offer several potential benefits, including enhancing growth, health, and disease resistance in cultured aquatic organisms. This approach has garnered attention for its potential to contribute to the long-term success and sustainability of aquaculture operations (Ringø and Song, 2016; Hoseinifar et al., 2016; Vijayaram et al., 2023 a, b). Synbiotics are crucial in enhancing intestinal health, growth, and overall performance in aquatic organisms. They represent a potential alternative to antibiotics in aquaculture, addressing concerns related to antibiotic resistance and ensuring health and food safety (Okey et al., 2018; Ghafarifarsani et al., 2021 b). Studies have shown notable improvements in various aspects of aquaculture, particularly in Pacific white shrimp, with the use of dietary synbiotics at a concentration of 3 g/kg for 56 days. These improvements include enhanced growth, feed utilization, intestinal health, and non-specific immunity. Interestingly, applying synbiotics by spraying onto the diet has demonstrated better performance compared to simply adding them during the pelleting process (Yao et al., 2021). As research in this field progresses, it is expected that more probiotic strains and prebiotic compounds will be tested, leading to a better understanding of their specific benefits for different aquaculture species. This continuous exploration and refinement of synbiotic applications hold promise to further enhance aquaculture practices' efficiency and sustainability.

Application of biogenic supplements in aquaculture

Herbals

Incorporating various botanical extracts into aquafeed supplements has shown promising results in enhancing antioxidant levels, growth performance, gene expression, immune response, and disease resistance in various cultured aquatic species.

Table 4. Summary of herbal feed supplements and their effects on aquatic animals

Herbal's local name and scientific name	Aquatic animal's local name and scientific name	Administration/dosages	Response	Duration of treatment	References
Turmeric (<i>Curcuma longa</i>)	African sharp-tooth catfish (<i>Clarias gariepinus</i>)	1%	Enhanced hematological parameters, reduces the activity of liver enzymes (ALT, AST, ALP), and boosts the immune response	8 weeks	Anene et al. (2021)
Turmeric rhizomes (TR), tuhau stems (TS), and betel leaves (BL)	Hybrid grouper (<i>Epinephelus fuscoguttatus</i> ♀ × <i>Epinephelus lanceolatus</i> ♂)	0.5%	Improved the growth, feed consumption, apparent digestibility, co-efficient of body protein, and lipid contents	8 weeks	Abang Zamhari et al. (2021)
Mojave yucca (<i>Yucca schidigera</i>)	European seabass (<i>Dicentrarchus labrax</i>)	0.75 mg/L ⁻¹	Improved the growth, survival, and hematological parameters	8 weeks	Fayed et al. (2019)
Citrus lemon peel by-product	Juvenile abalone (<i>Haliotis discus</i>)	50 g/kg	Significantly increased the growth performance and acted as a stress reducer	16 weeks	Dai and Cho (2022)

Olive leaf extract (1%) in common carp: Adding 1 g/kg of olive (*Olea europaea*) leaf extract to aquafeed supplements during a 60-day trial improved the immune system and increased survival against *E. tarda* in common carp (Zemheri-Navruz et al., 2019).

Turmeric (1%) in African sharp tooth catfish: Incorporating 1% turmeric (*Curcuma longa*) powder into aquatic feed enhanced hematological parameters, reduced liver enzyme activity, and boosted the immune response in African sharp tooth catfish (*Clarias gariepinus*) with no adverse effects (Anene et al., 2021).

Turmeric rhizomes, tuhau stems, and betel leaves (0.5%) in hybrid grouper: Inclusion of turmeric rhizomes, tuhau stems, and betel leaves at a concentration of 0.5% in aquafeed supplements significantly improved growth, feed consumption, apparent digestibility coefficient of body protein, and lipid contents of hybrid grouper compared to the control diet (Abang Zamhari et al., 2021).

Chinese yam (0.4%) in rainbow trout: Chinese yam (cinnamon vine; *Dioscorea oppositifolia* L.) extract at a 0.4% concentration in aquafeed supplements during an 8-week trial improved gut microbial composition, digestive enzymes, and immunomodulatory effects in rainbow trout (*Oncorhynchus mykiss*) (Wang et al., 2020).

Herbal cassava (15 mL) in common carp: Supplementing aquafeed with 15 mL of herbal *Manihot esculenta* Crantz (cassava) extract significantly enhanced the growth rate and decreased the feed conversion ratio in common carp (*Cyprinus carpio*) (Efiana et al., 2020).

Mojave yucca (0.75 mg/L) in European seabass: Administering 0.75 mg/L of *Yucca schidigera* (Mojave yucca) liquid extract with aquafeed supplements improved growth, survival, hematological and immunological parameters in European seabass (*Dicentrarchus labrax*) juveniles, while also reducing ammonium concentration in the water (Fayed et al., 2019).

Jujube (1%) in rainbow trout: Feeding rainbow trout (*Oncorhynchus mykiss*) with aquafeed supplements containing 1% jujube (*Ziziphus jujuba*) water extracts for 8 weeks improved immunity, digestive function, and gut microbial composition (Liu et al., 2021 a, b).

Citrus lemon peel by-product (50 g/kg) in juvenile abalone: Dietary inclusion of 50 g/kg of citrus lemon peel by-product into aquafeed supplements increased growth performance and acted as a stress reducer for juvenile abalone (*Haliotis*) during a 16-week feeding trial (Dai and Cho, 2022).

Ginkgo biloba extract (4 g/kg) in Nile tilapia: Adding *Ginkgo biloba* (maidenhair tree) extract at a concentration of 4 g/kg to aquafeed supplements during a 60-day feeding trial improved antioxidative status, immune system, and reduced inflammation in Nile tilapia (Zheng et al., 2022) (Table 4).

Biogenic supplements from different sources

Section 1: Animal-derived biogenic supplements

The utilization of animal-derived supplements in aquaculture is gaining attention due to their nutritional benefits and potential to improve fish health and performance. Taurine and selenium yeast are examples of such supplements that have been thoroughly researched (Sampath et al., 2020; Wang et al., 2019). The biogenic dietary supplementary role is summarized in Figure 1; Table 5.

Section 2: Plant-derived biogenic supplements

Plant-derived supplements, particularly microalgae and seaweed, are widely used in aquaculture diets. Microalgae species like *Chlorella* sp. and *Nannochloropsis* sp. are rich sources of nutrients and have demonstrated improvements in growth, immunity, and nutrient utilization in aquatic animals (Becker, 2013; Adissin et al., 2019).

Section 3: Microbial-derived biogenic supplements

Microbial-derived supplements, including probiotics, play an important role in promoting gut health and

disease resistance in aquaculture species. *Tetraselmis suecica* and *Gracilaria arcuata* are examples of microbial supplements that have been studied for their efficacy in enhancing fish health and performance (Sharawy et al., 2020; Younis et al., 2018).

Section 4: Cultivation and application of microalgae in aquaculture

Microalgae cultivation is essential for sustainable aquaculture practices. Studies have demonstrated the application of microalgae in wastewater treatment and nutrient management in aquaculture systems (Guldhe et al., 2017; Tejido-Núñez et al., 2020).

Probiotics

Probiotics derived from various sources like the gut, water, soil, food, and primary/secondary hosts have a crucial role in the aquatic industry. They offer several advantages to the host, including enhancing gut microbiota composition, promoting growth, boosting immune gene expression, improving immune system responses, increasing disease resistance, and enhancing water quality in aquaculture (Tang et al., 2018; Balasubramanian et al., 2018; Makridis et al., 2021; Sharifuzzaman and Austin, 2017). Probiotics exhibit essential characteristics such as acid tolerance, bile salt tolerance, auto-aggregation, antimicrobial activity, susceptibility to antibiotics, and the ability to

bind to the mucosal surface. These traits are significant factors when identifying potential probiotic candidates (Hosain and Liangyi, 2020). Probiotics employ various mechanisms of action, including antimicrobial activity against harmful pathogens, the production of beneficial metabolites, the synthesis of vitamins, the ability to adhere to the gut lining, and the enhancement of the immune system (Pushparaj et al., 2022). Various types of probiotics are isolated from salmon and black tiger shrimp hatcheries, encompassing species such as *Aeromonas* sp., *Vibrio* sp., *Pseudomonas* sp., and groups of Coryneforms. These probiotics exhibit potential antiviral activity against the Infectious Hematopoietic Necrosis Virus (IHNV) in *Oncorhynchus masou* (masu salmon) (Loh, 2017). Dietary supplementation of probiotics stimulates the immune response to help control diseases in cultured aquatic species. Probiotics like *Aeromonas veronii*, *Vibrio lentus*, and *Flavobacterium* activate both cellular and humoral-mediated immunity by increasing the production of immune factors such as TNF, IL-1b, and lysozymes in carp species (Dawood et al., 2018). Hlordzi et al. (2020) reported that *Bacillus* species significantly improved water quality parameters such as pH, DO, conductivity, BOD, COD, and more. They also found that *Bacillus* species influenced the microbial composition in fish culture.

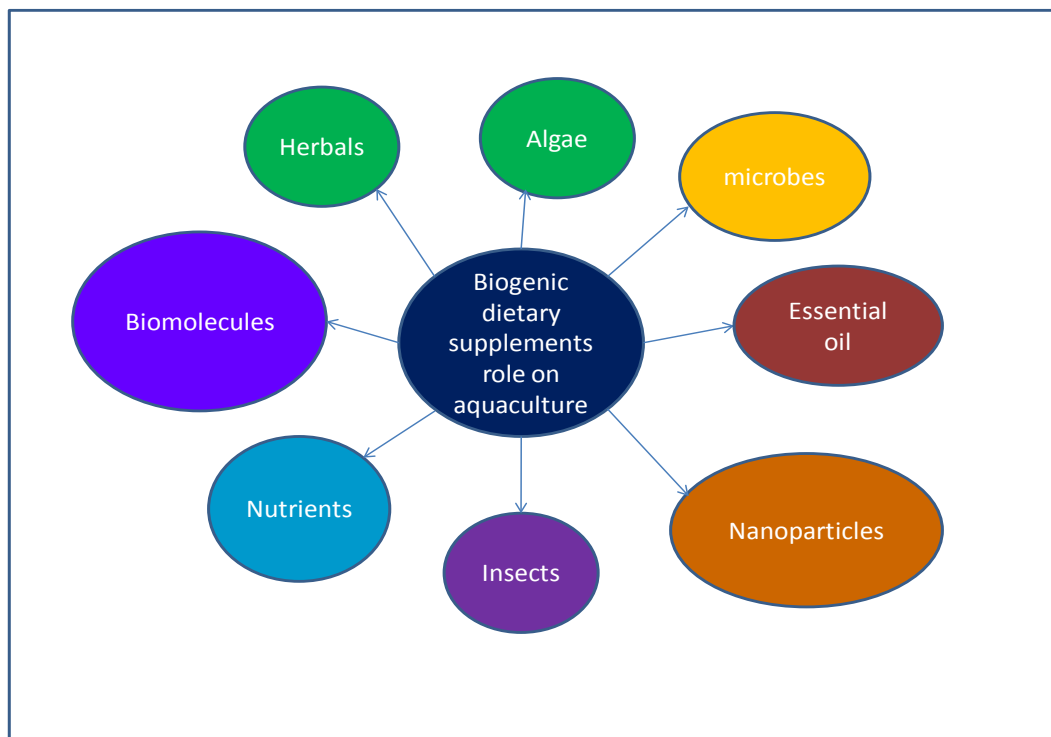


Figure 1. Biogenic dietary supplements' role in aquaculture

Table 5. Applications of biogenic dietary supplements in aquaculture

Biogenic substances	Scientific name of biogenic substances	Aquatic animals Scientific name	Aquatic animals Local name	Administration	Response	References
1	2	3	4	5	6	7
Turmeric powder	<i>Curcuma longa</i>	<i>Clarias gariepinus</i>	African sharp tooth catfish	1%	Improved hematological parameters	Anene et al. (2021)
Chinese yam	<i>Dioscorea oppositifolia</i> L.	<i>Oncorhynchus mykiss</i>	Rainbow trout	0.4% for 8 weeks	Increased gut microbial composition, digestive enzymes, and immunomodulatory effects	Wang et al. (2020)
Mojave yucca	<i>Yucca schidigera</i>	<i>Dicentrarchus labrax</i>	European seabass	0.75 mg/L ⁻¹	Increased stress tolerance effect against ammonia	Fayed et al. (2019)
Maidenhair tree	<i>Ginkgo biloba</i>	<i>Oreochromis niloticus</i>	Nile tilapia	1 and/ or 4 g/kg for 60 days	Improved antioxidative status, immune system, and suppression of inflammation	Zheng et al. (2022)
Marine microalgae	<i>Tetraselmis suecica</i>	<i>Litopenaeus vannamei</i>	Pacific white shrimp	7.5 g/kg	Improved growth and nutrient utilization	Sharawy et al. (2020)
Microalgae	<i>Chlorella vulgaris</i>	<i>Macrobrachium rosenbergii</i>	Giant freshwater prawn	4% and 15% for 50-day trial	Better immune response and resistance of <i>M. rosenbergii</i> postlarvae against <i>A. hydrophila</i> infection	Maliwat et al. (2017)
Microalgae	<i>Scenedesmus obliquus</i>	<i>Anarhichas minor</i>	Spotted wolffish	4% for 12-week feeding trial	Increased muscle growth	Knutsen et al. (2019)
Microalgae	<i>Gracilaria arcuata</i>	<i>Oreochromis niloticus</i>	Nile tilapia	20% for a 12-week feeding trial	Improved growth performance	Younis et al. (2018)
Microalgae	<i>Arthrospira</i> sp.	<i>Sparus aurata</i>	Gilthead seabream	4% for 128-day feeding trial	Enhanced muscle pigmentation and antioxidant activity	Galafat et al. (2022)
Microbes	<i>Bacillus pumilus</i>	<i>Oreochromis niloticus</i>	Nile tilapia	1.85 × 10 ⁵ for 84-day feeding trial	Enhanced the growth performance, intestinal histological morphometric, immune response, hematological, biochemical blood, metabolic gene expression and intestinal bacterial flora	Hassaan et al. (2021)
Microbes	<i>Bacillus</i> sp. R2 and <i>Planococcus</i> sp. R11	<i>Sparus aurata</i>	Sea bream	1:1 for 40-day feeding trial	Improved growth performance and survival	Ghohane et al. (2020)
Microbes	<i>B. thuringiensis</i> QQ1 and <i>B. cereus</i> QQ2	<i>Lates calcarifer</i>	Asian seabass	10 ⁶ cfu/g for 8 weeks	Enhanced immune response, antioxidant and disease resistance	Ghaneil-Motlagh et al. (2021)
Microbes	<i>Streptomyces antibioticus</i> EW1 (MH301104)	<i>Heteropneustes fossilis</i>	Freshwater catfish	NM	Improved growth, digestion, nutrient utilization and survival	Das et al. (2021)
Microbes	<i>Saccharomyces cerevisiae</i> coupled with <i>Lactobacillus casei</i>	<i>Lates calcarifer</i>	Barramundi	1% for 56-day feeding trial	Improved the growth, immune response and gut health	Siddik et al. (2022)
Yellow mealworm	<i>Tenebrio molitor</i>	<i>Oncorhynchus mykiss</i>	Rainbow trout	50% for 75 days	Improved growth performance	Gasco et al. (2014)
Maggot	<i>Musca domestica</i>	<i>Lates calcarifer</i>	Barramundi	300 g/kg for 8 weeks	Improved physiological responses	Lin et al. (2017)
Grasshopper	<i>Caelifera</i>	<i>Clarias gariepinus</i>	African catfish	25%	Improved growth performance	Alegbeleye et al. (2012)
Migratory locust	<i>Locusta migratoria</i>	<i>Oreochromis niloticus</i>	Nile tilapia	25%	Improved growth performance	Emehinaiyi et al. (2012)

Table 5 – contd.

1	2	3	4	5	6	7
Migratory locust	<i>Locusta migratoria</i>	<i>Oreochromis niloticus</i>	Nile tilapia		Improved growth performance	Emehinaiyi et al. (2012)
Lemon peel essential oil	<i>Citrus limon</i>	<i>Oncorhynchus mykiss</i>	Rainbow trout	25% 400 mg/kg for 96 h	Decreased the adverse effect of deltamethrin (DMN) pesticide	Amiri Resketi et al. (2021)
Oregano essential oil	<i>Origanum onites</i> L.	<i>Oncorhynchus mykiss</i>	Rainbow trout	3.0 mL/kg for 90 days	Enhanced disease resistance	Diler et al. (2017)
Olive pomace oil	<i>Olea europaea</i>	<i>Oncorhynchus mykiss</i>	Rainbow trout	12% for 60 days	Increased the immune responses and made <i>O. mykiss</i> more resistant to infection by <i>L. garvieae</i>	Yilmaz et al. (2020)
Konjac glucomannan	<i>Amorphophallus konjac</i>	<i>Trachinotus ovatus</i>	Golden pompano	1% for 60 days	Improved growth, feed efficiency, antioxidant capacity, hepatic lipid metabolism and inflammatory response	Li et al. (2021)
Methionine	NA	<i>Larimichthys crocea</i>	Large yellow croaker	0.6–1.2% for 10 weeks	Enhanced antioxidant and lipid metabolism level	Li et al. (2021)
Lysine	NA	<i>Ctenopharyngodon idella</i>	Grass carp	14.18 g/kg for 60-day feeding trial	Enhanced immune response and molecular mechanism in skin, head kidney and spleen	Hu et al. (2021)
Histidine	NA	<i>Ctenopharyngodon idella</i>	Grass carp	7.9 g/kg diet for 8 weeks	Improved growth and flesh quality	Wu et al. (2020)
Taurine	NA	<i>Acipenser ruthenus</i>	Sterlet	30 g/kg for 70 days	Enhancement of growth performance, hepatic, digestive, and antioxidant enzyme activities	Bavi et al. (2022)
Pepsin	NA	<i>Pangasianodon hypophthalmus</i>	Striped catfish	0.50 g/kg for 90 days	Increased production performance	Islam et al. (2021)
Pyrrroloquinoline quinone	NA	<i>Pelteobagrus fulvidraco</i>	Yellow catfish	4.92 mg/kg for 56 days	Improved the growth performance, serum biochemical parameters, antioxidant status, and growth-related gene expressions	Shi et al. (2022)
Polyphenol	NA	<i>Cyprinus carpio</i>	Common carp	400 mg/kg for 70 days	Increased mineral absorption	Hussain et al. (2022)
β-glucans	NA	<i>Litopenaeus vannamei</i>	Pacific white shrimp	10 mg/kg	Improved body composition and hematology	
Curcumin	NA	<i>Channa argus</i>	Northern snakehead	400 mg/kg for 28-day trial	Improved growth, intestinal health, immune response, and resistance against <i>Vibrio harveyi</i> infections	Ayiku et al. (2020)
Selenium nanoparticles	NA	<i>Pagrus major</i>	Red sea bream	1–2 mg/kg for 45-day feeding trial	Reduced DEL-induced oxidative stress, inflammation, and cell apoptosis in <i>C. argus</i> via Nrf2 and NF-κB signaling pathways	Kong et al. (2021 a, b)
Copper nanoparticles	NA	<i>Macrobrachium rosenbergii</i>	Freshwater prawn	20 mg/kg for 90 days	Maintained overall growth response	Dawood et al. (2019)
Zinc nanoparticles	NA	<i>Pangasius hypophthalmus</i>	Striped catfish	20 mg/kg	Regulated better survival, growth and immune response of <i>M. rosenbergii</i> PL	Muralisankar et al. (2016)
					Improved stress tolerance effect against abiotic and biotic conditions	Kumar et al. (2018)

However, the effectiveness of these improvements depends on the method of application, the selection of the specific *Bacillus* strain, and the availability of nutrients in the aquatic environment. Supplementing the diet of shrimp (*P. vannamei*) with probiotics CDM8 and CDA22 for 21 days significantly decreased pathogenic *Vibrio* counts in the hindgut and increased survival rates, attributed to the secretion of catalase. The study concluded that these probiotics when used in 21-day feeding trials, enhance disease resistance against acute hepatopancreatic necrosis disease (AHPND) caused by *Vibrio parahaemolyticus* in shrimp aquaculture (Wang et al., 2018). According to FAO (2020), probiotics exhibit strong inhibitory activity against pathogens and enhance disease resistance in various fish species, including Atlantic cod (*Gadus morhua*), Nile tilapia (*Oreochromis niloticus*), rainbow trout (*Oncorhynchus mykiss*), common carp (*Cyprinus carpio*), and sea bass (*Lates calcarifer*) juveniles. It is worth noting that Nile tilapia (*Oreochromis niloticus*) holds significant importance as a major contributor to global aquaculture production. *Corynebacterium ammoniagenes* (at a level of 10–20%) and *Methylobacterium extorquens* protein have the potential to serve as substitutes for fishmeal in shrimp diets. These alternative protein sources can help reduce the reliance on fishmeal in aquaculture feeds (Chumpol et al., 2018). Incorporating *Enterococcus faecium* into the diet for 7 and 14 days results in significantly enhanced final weight, final biomass, weight gain, and respiratory burst activity in tilapia (*Oreochromis niloticus*). Furthermore, it helps maintain the defense mechanisms of the immune system in these fish (Changpasert et al., 2022). Incorporating plant-based protein into the diet along with *Bacillus pumilus* (at a concentration of 1.85×10^5 cfu/kg) and protease (at 0.5 g/kg) during an 84-day feeding trial significantly improves the growth and feed intake in tilapia (*Oreochromis niloticus*). The combination of *B. pumilus* and exogenous protease offers synergistic effects that benefit the fish (Hassaan et al., 2021; Yang et al., 2021). Oral administration of probiotic *Lactobacillus plantarum* at a concentration of 2×10^7 cfu/g in the diet for 72 days, following yersiniosis vaccination, significantly enhances the growth performance of rainbow trout (*Oncorhynchus mykiss*). It also helps maintain gut microbiota, and digestive enzyme activity and improves nutrient digestibility and utilization (Soltani et al., 2019).

Bio-encapsulated *Planococcus* at a 1% concentration in live food culture (rotifers and *Artemia*) during a 40-day feeding trial significantly improved the growth, survival, digestibility, and biochemical indices of gilthead sea bream (*Sparus aurata*) (Ghohame et al., 2020). Adding the probiotic *Paenibacillus ehimensis* NPUST1 to the diet during a 2-month feeding trial significantly enhances the growth performance, immunity, and infection resistance in Nile tilapia (*Oreochromis niloticus*) (Chen et al., 2019). Probiotics *B. thuringiensis* QQ1 and *B. cereus* QQ2 at a concentration of 10^9 cfu/g in the diet during an 8-week feeding trial significantly enhances immunity

and antioxidant levels, helping to suppress *Vibrio alginolyticus* infections in Asian seabass (*Lates calcarifer*). However, further research is needed to clarify the precise mechanisms associated with the QQ system and its role in protecting fish from infections caused by *Vibrio* pathogens (Ghane-Motlagh et al., 2021). Supplementing the diet with probiotic *Pediococcus pentosaceus* MR001 at a concentration of 10^9 cfu/g significantly increases feed utilization, growth, digestive enzyme activity, and disease resistance against vibriosis in shrimp (*Litopenaeus vannamei*). The study concludes that *P. pentosaceus* MR001 is an effective and valuable feed additive for aquaculture (Wanna et al., 2021). In a 45-day feeding trial, the dietary administration of the probiotic *Streptomyces antibioticus* EW1 (MH301104) demonstrated better activity compared to a diet incorporating *B. cereus*. The probiotic *Streptomyces antibioticus* EW1 (MH301104) significantly improved growth performance, digestibility, and nutrient intake, and reduced the mortality rate of juvenile catfish (*Heteropneustes fossilis*) (Das et al., 2021). Probiotics such as *Lactococcus lactis* L19 and *Enterococcus faecalis* W24 at a concentration of 1.0×10^8 cfu/g in the diet during a 56-day feeding trial significantly increase digestive enzyme activity, improve intestinal microbiota, enhance the intestinal morphology antioxidant capacity of Northern snakehead (*Channa argus*). Dietary supplementation of the probiotic *L. lactis* L19 is more efficient in providing protection compared to W24. Probiotic dietary additives demonstrate a more beneficial response in cultured fish species (Kong et al., 2021 a, b). In a study by Siddik et al. (2022), a dietary combination of probiotics, specifically *Lactobacillus casei* and *Saccharomyces cerevisiae* at a 1% concentration, was administered to juvenile barramundi during a 56-day feeding trial. This combination significantly enhanced growth, and feed utilization, maintained microbiota composition, and improved the immune response in the juvenile fish.

Further research is required to fully comprehend the exact mechanisms of action in the gut region of fish. However, dietary inclusion of two *Bacillus* strains, *B. cereus* KAF124, and *B. thuringiensis* KAF135, has shown significant improvements in growth, immunity, antioxidant activity, digestive enzymes, disease resistance, antimicrobial activity, and the regulation of gut microbiota composition in marine fish *Moolgarda seheli* (Husain et al., 2022). Probiotic *B. velezensis* GY65 in the diet significantly improves growth performance, immunity, and amylase activity, and reduces the pathogenic load in mandarin fish (*Siniperca chuatsi*) (Wang et al., 2021 a, b).

Essential oils and plant oils

Incorporating lemon peel essential oil (LPEO) into the diet at a concentration of 400 mg/kg significantly reduced the negative effects of deltamethrin (DMN) pesticide exposure and enhanced growth indices and carcass composition in juvenile rainbow trout (*Oncorhynchus mykiss*) (Amiri Resketi et al., 2021). Dietary supplementation of microencapsulated carvacrol, garlic, and thymol

enhanced the activation of the protein biosynthetic process in the gills of gilthead sea bream (*Sparus aurata*), utilizing plant-derived supplements (Firmino et al., 2020). Including Greek oregano (*O. onites*) essential oil at a concentration of 3.0 mL/kg in the diet during a 90-day trial significantly improved the survival rate of rainbow trout (*Oncorhynchus mykiss*) against *L. garvieae*, a pathogenic bacterium, which is also a plant-derived supplement (Diler et al., 2017). In a study conducted by Baba et al. (2017), dietary incorporation of argan oil derived from the argan tree (*Argania spinosa*) at various concentrations (0%, 0.5%, 1%, or 2%) significantly increased immunohematological and biochemical responses. Additionally, this dietary supplementation improved disease resistance against *L. garvieae* in Nile tilapia (*Oreochromis niloticus*), which is another example of plant-derived supplements. Including olive pomace (*Olea europaea*) oil in the diet has been shown to significantly improve the antioxidant capacity and infection tolerance in rainbow trout (*Oncorhynchus mykiss*), also categorized under plant-derived supplements (Yilmaz et al., 2020). In a study by Baba et al. (2016), it was found that including 0.5% citrus lemon peel essential oil in the diet significantly increased the antioxidant capacity and disease resistance against *E. tarda* in Nile tilapia (*Oreochromis niloticus*), representing plant-derived supplements.

Incorporating essential oil from sweet basil (*Ocimum basilicum*) at a concentration of 2.0 mL per kilogram of diet for 48 days of feeding trials resulted in improved growth performance in pirarucu juveniles (*Arapaima gigas*), which is another example of plant-derived supplements (Chung et al., 2020). Including the essential oil of ginger (*Zingiber officinale*) (EOZO) at a concentration of 0.5 mL in the diet during a 60-day feeding trial enhanced the growth activity, increased intestinal villi size, and improved hematological variables in Nile tilapia (*Oreochromis niloticus*), which falls under plant-derived supplements.

Nutrients

Animal-derived supplements

Methionine (MET) in the diet at concentrations ranging from 0.6% to 1.2% during 10 weeks of a feeding trial resulted in improved serum lipid profiles and a reduction in the size and number of liver lipid droplets in juvenile large yellow croaker (*Larimichthys crocea*), representing a functional supplement (Li et al., 2021).

Glutamine and glutamate at a concentration of 3% in the diet significantly increased growth performance, specific and non-specific immune responses, and skeletal muscle growth in fish, classified as functional supplements (Li et al., 2021).

Lysine supplement at a concentration of 14.18 g/kg in the diet for a 60-day feeding trial significantly increased lysozyme, acid phosphatase (ACP), and complement C3 activities in the gut region of grass carp (*Ctenopharyngodon idella*), representing a functional supplement (Hu et al., 2021).

Tryptophan at concentrations of 1.28% and 2.56% for a 7-day feeding trial under stress conditions significantly increased growth response and improved thermal and salinity stress resistance in Nile tilapia (*Oreochromis niloticus*), categorized as a functional supplement (Vieira et al., 2021).

Histidine at a concentration of 7.9 g/kg in the diet for an 8-week feeding trial significantly enhanced growth activity and digestive enzyme activity in grass carp (*Ctenopharyngodon idella*), classified as a functional supplement (Wu et al., 2020).

Taurine was included at a concentration of 1% in the feed; however, there were no significant changes observed in various growth and body composition parameters in striped bass (*Morone chrysops* × *M. saxatilis*), indicating that taurine supplementation at this level did not have a significant impact on the measured parameters in this particular study (Suehs and Gatlin III, 2021). In a 70-day feeding trial, taurine at a concentration of 30 g/kg considerably enhanced hepatic, digestive, and antioxidant enzyme activity in *A. rupestris*, classified as a functional supplement (Bavi et al., 2022).

Plant-derived supplements

Konjac glucomannan at a concentration of 1% in the diet for 60 days in aquafeed supplements significantly increased growth performance, antioxidant levels, lipid metabolism, and immune response in juvenile golden pompano (*Trachinotus ovatus*), categorized as a functional supplement (Li et al., 2021).

Microbial-derived supplements

Incorporating sulfate-based alginate polysaccharide (SAP) at a concentration of 1.91% in the diet during a 56-day feeding trial significantly improved growth, serum antioxidant levels, nonspecific immunity, intestinal health, and disease tolerance in Pacific white shrimp (*Litopenaeus vannamei*), representing a functional supplement (Chen et al., 2022).

Bioactive molecules

Animal-derived supplements

Pepsin at a concentration of 0.50 g/kg had a positive influence on the growth, feed consumption, blood physiology, and potentially water quality in the culture of striped catfish, representing a functional supplement (Islam et al., 2021).

Hydroxyproline (Hyp) at a concentration of 1% had multiple positive effects on Chinese perch (*Siniperca chuatsi*), including increased growth, improved muscle quality, higher collagen content, enhanced nutritional value, and improved digestive system activity, classified as a functional supplement (Feng et al., 2022).

Lactoferrin at a concentration of 100 mg/kg in fish feed for a one-week feeding trial had a positive impact on the immune system in diverse fish species such as gold-

fish (*Carassius auratus*), rainbow trout (*Oncorhynchus mykiss*), Atlantic salmon (*Salmo salar*), red sea bream (*Pagrus major*), and Asian catfish (*Pangasius hypophthalmus*), categorized as a functional supplement (Roy et al., 2020).

The oral dietary administration of peptidoglycan at a concentration of 0.2 mg/kg had a significant positive effect on the health and disease resistance of kuruma shrimps (*Marsupenaeus japonicas*), functioning as a dietary supplement (Kondo et al., 2021).

Plant-derived supplements

Polyphenols at a concentration of 400 mg/kg had multiple positive effects on common carp (*Cyprinus carpio*) fingerlings, including increased growth, improved feed conversion ratio, enhanced antioxidant status, and strengthened immunological parameters, classified as a functional supplement (Hussain et al., 2022).

Quercetin at concentrations of 0.5 or 1.0 g/kg notably reduced excess fat deposition in *Lateolabrax maculatus* (Asian sea bass) tissues stimulated by the intake of a high-fat diet (HFD), representing a functional supplement (Dong et al., 2021).

Microbial-derived supplements

β -glucans at a concentration of 10 mg/kg in aquafeed supplements for 56 days of feeding trials increased expression level to control the immune function and also blood neutrophils, oxidative radical production, and superoxide anion production in activated macrophages of white leg shrimp (*Litopenaeus vannamei*) juveniles, categorized as a functional supplement (Ayiku et al., 2020).

Microbial levan at 25 g/kg in aquafeed supplement significantly enhanced innate immune response, growth, survival, disease resistance, and thermal stress tolerance and also reduced loads of total viable aerobic bacteria and *Vibrio* spp. in the gut region of orange-spotted grouper (*Epinephelus coioides* H.), representing a functional supplement (Mohan et al., 2020).

Clostridium autoethanogenum protein (CAP) at 200 g/kg in fish feed significantly improved growth performance, serum chemical parameters, antioxidant status, and histopathological examination of the liver and midgut in juvenile Jian carp (*Cyprinus carpio*), functioning as a dietary supplement (Li et al., 2021).

Nanoparticles

Incorporating nanoparticle supplements into aquatic feed is an innovative approach that has shown significant potential in enhancing the quality of aquaculture. These nanoparticles have been demonstrated to improve survival rates, antioxidant levels, growth performance, and immune responses in aquatic species. However, it is crucial to note that excessive nanoparticle supplementation can potentially lead to side effects in aquatic organisms (Muralisankar et al., 2014; Ashouri et al., 2015; El Basuini et al., 2016; Faiz et al., 2015; Vijayakumar et al., 2019; Rashidian et al., 2021; Elabd et al., 2022).

Selenium nanoparticles

Selenium nanoparticles (1–2 mg/kg diet) for a 45-day feeding trial notably improved the immune system, total protein content, and antioxidant activities in red sea bream (*Pagrus major*), indicating their potential as a valuable dietary supplement in promoting fish health (Dawood et al., 2019).

Qin et al. (2016) demonstrated that selenium nanoparticles at 0.2 mg/kg for 60 days of feeding trials significantly increased the immune system, disease resistance, and resistance against hypoxia stress in Chinese mitten crab (*Eriocheir sinensis*), highlighting their role in enhancing the resilience of aquatic species.

Gold nanoparticles

Oral dietary administration of Au-NPs (2 μ g/g) increased the immune system, antioxidant levels, survival, and disease resistance against *V. parahaemolyticus* in shrimp (*Litopenaeus vannamei*), suggesting the potential of gold nanoparticles as a beneficial dietary supplement aimed at promoting shrimp health (Na-Phatthalung et al., 2018).

Copper nanoparticles

Copper nanoparticles at 20 mg/kg in a 90-day feeding trial significantly enhanced growth, survival, and immune response in postlarval stages of the freshwater prawn (*Macrobrachium rosenbergii*). However, elevated doses (40–80 mg/kg) may lead to toxic effects, emphasizing the importance of proper dosage management (Muralisankar et al., 2016).

Silver nanoparticles

Silver nanoparticles considerably enhanced growth response, protease, and metalloprotease activity in zebrafish (*Danio rerio*) and rainbow trout (*Oncorhynchus mykiss*), suggesting their potential to optimize growth and nutrient utilization in aquaculture practices (Sarkar et al., 2015 b; Mirghaed et al., 2018).

Zinc nanoparticles

Zinc nanoparticles at 20 mg/kg enhanced growth and immune system response against abiotic and biotic stress conditions in shark catfish (*Pangasius hypophthalmus*), highlighting their potential benefits in promoting fish health and resilience (Kumar et al., 2018).

Zinc oxide nanoparticles

Zinc oxide nanoparticle supplements demonstrated better disease resistance activity against multi-drug resistant bacteria that affect fish such as *A. veronii* and *S. maltophilia* in aquaculture, showcasing their potential as effective nano antibiotics (Pati et al., 2021; Ghafarifar-sani et al., 2023). The biogenic dietary supplementary role is summarized in Figure 1.

Conclusion

This study provides a comprehensive summary of the benefits of biogenic-mediated dietary supplements in aq-

uaculture, highlighting their potential to improve growth, antioxidant levels, immune response, disease resistance, stress tolerance, and water quality. These supplements, developed from natural sources, offer an eco-friendly, non-toxic, and cost-effective alternative to traditional methods such as antibiotics, chemotherapeutics, and vaccines, which often lead to side effects in both aquatic animals and humans. The manuscript emphasizes that while the optimal concentration of these supplements enhances physiological responses, exceeding this concentration does not further improve outcomes. To strengthen the study, it is recommended that future research be directed toward exploring the optimal dosage of biogenic supplements across different fish species, as variations in species may affect efficacy. Additionally, large-scale field trials are essential to validate the results obtained in laboratory settings and to confirm their real-world applicability. This study sets the foundation for ongoing research aimed at developing new biogenic supplement products, which have the potential to revolutionize sustainable aquaculture practices.

Conflicts of interest/Competing interests

There is no conflict of interest to declare.

Consent for publication

All authors give consent for publication.

Availability of data and material

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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