Indian J Anim Health (2025), 64(2) : 219- 230
DOI: https://doi.org/10.36062/ijah.2025.08425

Review Article

Natural bioactive compounds in aquaculture: A sustainable approach using medicinal plants and marine resources

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Abstract

The incorporation of bioactive compounds from both medicinal plants and marine species into aquaculture is garnering significant attention as a strategy to enhance sustainability and health benefits. The utilization of medicinal plants has been validated as both safe and natural, exhibiting minimal adverse effects during their application, thereby indicating their potential as viable alternatives to traditional antibiotics and synthetic additives in aquafeed formulations. Bioactive substances, encompassing antioxidants, antimicrobials, and anti-inflammatory agents derived from medicinal plants, have demonstrated beneficial impacts on the health and biosecurity of aquaculture species, thus promoting sustainable aquaculture production practices. Furthermore, the bioactive components extracted from the remarkably diverse chemical profiles of natural medicinal plant compounds exhibit biological efficacy linked to their antioxidant and immunostimulant characteristics. The advantages derived from unique marine environments yield an even broader array of bioactive compounds derived from algae and invertebrates, serving as functional food sources. With the escalating global demand for fish and fishery products annually, the integration of these natural compounds into aquaculture not only addresses food security concerns but also mitigates environmental repercussions, ultimately fostering a more sustainable aquaculture framework.

Keywords: Aquaculture, Aquafeed, Bioactive compounds, Immunostimulant

Highlights

- Plant derived compounds are beneficial in aquaculture practices
- Bioactive compounds serve as potential functional food sources for fish
- Bioactive compounds possess antioxidant, immunomodulatory, and antimicrobial properties

INTRODUCTION

The Global Report on Food Crises (GRFC) 2024 (Food Security Information Network [FSIN], 2024) highlights the alarming state of food insecurity worldwide, revealing that in 2023, approximately 281.6 million individuals across 59 countries faced significant challenges related to hunger. This marks an increase of 24 million from the previous year, underscoring the urgent need for action as 1 in 5 people assessed require immediate assistance. Projections indicate a continuous rise in the global population, potentially reaching 10.3 billion by the mid-2080s. By 2030, it is estimated that 750 million people will still lack access to sufficient food, a fundamental human right (von Grebmer et al., 2023). Amidst these challenges, aquaculture emerges as a promising solution to address global food security concerns, standing out as a rapidly expanding industry (Naylor et al., 2023). This critical stage in the lives of young individuals is marked by notable barriers, such as hunger and food insecurity (von Grebmer et al., 2023).

Food safety in aquaculture is closely linked to bioactive compounds found in fish and other aquatic animals, which offer health benefits beyond their nutritional role (Anthes & De Schutter, 2018). Antioxidants, antimicrobials, and anti-inflammatory agents are gaining recognition for their positive impact on aquaculture sector (Mutalipassi et al., 2021). These compounds reduce the need for antibiotics, benefiting the environment and promoting sustainable farming practices (Pradeepkiran, 2019; Bondad-Reantaso et al., 2023). They also improve aquatic organism health and fish safety, making seafood products more valuable as global demand for seafood increases (Boland et al., 2013; Šimat et al., 2020).

Optimizing the use of available spatial and resource

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capacities is crucial for enhancing production efficiency and promoting sustainability (Food and Agriculture Organization of the United Nations [FAO], 2024). The growing global demand for fish and fishery products stems from the health benefits of these foods, particularly their high mineral and protein content, making them essential for a balanced diet (Tejpal et al., 2022). The aquaculture industry plays a key role in meeting the increasing need for protein-rich food, with global production reaching 223.2 million tonnes in 2022, including 185.4 million tonnes of aquatic animals and 37.8 million tonnes of algae for human consumption (FAO, 2024). Given the importance of fish and seafood in global diets, ensuring the sustainable development of aquaculture is vital (Prakash et al., 2023; Chavan et al., 2024; Patekar et al., 2025; Routroy et al., 2025). However, the growth of this industry raises concerns about the safety and quality of aquaculture products. This highlights the need for stringent regulations to ensure consumer confidence and protect public health from potential risks associated with these products.

Fig. 1. Roles of bioactive compounds in aquatic animal health and growth

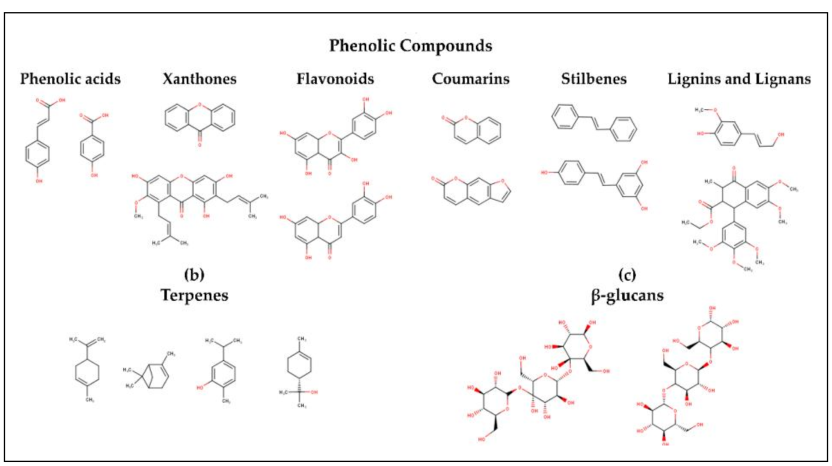

Fig. 2. Chemical structure of key bioactive (a) phenolic compounds, (b) terpenes, and (c) β-glucans (Leyva-López et al., 2020)

Bioactive compounds

Bioactive compounds, which can be comprehensively defined as naturally occurring chemical entities that are predominantly found within an extensive array of food sources, exhibit a remarkable and profound capacity to significantly influence various metabolic pathways; consequently, these compounds play an exceptionally instrumental role in the enhancement and promotion of overall health as well as the well-being of individuals. The advantageous properties exhibited by these compounds are diverse and multifaceted, encompassing a plethora of beneficial effects that not only include their potent antioxidant capabilities but also extend to the intricate modulation of enzyme activities, the precise regulation of receptor functions, and their remarkable ability to exert control over the complex processes of gene expression (Correia et al., 2012). Extensive contemporary research examines a diverse array of bioactive compounds and their potential health benefits (Fig. 1). Examples of phytosterols, flavonoids, carnitine, coenzyme Q, carotenoids, phytoestrogens. Choline, polyphenols, glucosinolates, and taurine are considered important for benefiting and improving health. Since vitamins and minerals have valuable chemicals and many effects, they are regarded as bioactive compounds in the area of nutrition science and human health. Therefore, further research is important to better explain how particular bioactive substances impact our bodies and what the best ways are to benefit from them.

Phenolic compounds are a wide range of biologically active molecules valued for their many functions, especially for combating oxidative stress, fighting inflammation, preventing various microbial diseases, preventing cancer, and supporting immune health and the balance of gut bacteria (Fig. 2) (Leyva-López et al., 2020). Moreover, the detailed chemical and structural aspects of phenolic compounds are key to their biological activities, mainly their ability to fight oxidative stress, which is essential in hindering various harmful diseases (Zhang et al., 2022). The number and location of hydroxyl functional groups, along with conjugated double bonds and electron delocalization within their pathways, strongly affect phenolic compounds' ability to act against free radicals and contribute hydrogen atoms (Leicach & Chludil, 2014). Apart from their antioxidant effects, phenolic compounds interact with receptors, transcription factors, enzymes, and different membrane proteins, indicating they are involved in many cellular activities (Fraga et al., 2010).

Sources of bioactive compounds as feed additive: Bioactive compounds extracted or used as a whole from marine derivatives, fishery by-products, plant sources, and agricultural waste, etc.

Marine derivative: The marine ecosystem, one of the least explored biological reserves, is home to a vast array of organisms with unique biological features, many of which remain understudied. Algae and microalgae, in particular, have gained recognition as valuable sources of bioactive compounds, ideal for incorporation into functional foods that enhance nutrition and promote health benefits (Hayes, 2012). These compounds, derived from marine organisms, attract significant attention due to their unique characteristics shaped by the marine environment's dynamic conditions-salinity, temperature fluctuations, and varying light exposure. This environment influences the biosynthesis of these extraordinary compounds.

Exploring bioactive substances from marine sources holds immense potential for advancing our understanding of marine biology and creating innovative functional foods that can enhance global health. Additionally, natural products from marine invertebrates and algae have been instrumental in modern medicine, offering therapeutic efficacy and pharmacological potential, with promising opportunities for further exploration (Sigwart et al., 2021). The marine ecosystem is a rich reservoir of biomolecules with bioactive properties, including antioxidant, anti-parasitic, antimicrobial, anti-cancer, antiviral, anti-fibrotic, and anti-inflammatory effects, which are increasingly recognized for their therapeutic value. As research continues, the marine ecosystem's vast potential in health and medicine remains a promising field for future exploration and innovation.

Microalgae /seaweed: Algae are photosynthetic organisms that thrive in aquatic ecosystems, serving as primary producers and forming the foundation of food chains. Algae are classified into microalgae, which are microscopic, and macroalgae, or seaweeds, which are larger and more visible (Chandini et al., 2008). Brown, red, and green macroalgae are used in food and medicine for their beneficial properties. Brown algae, identified by the pigment fucoxanthin, can grow up to 45 meters, with 1,500-2,000 species worldwide (Kadam et al., 2015). Microalgae are gaining attention for their carotenoids and chlorophyll, which have antioxidant, antifungal, antibacterial, and anti-inflammatory properties. Phlorotannins from microalgae are used in functional foods to treat high blood sugar and cholesterol (Rani & Yadav, 2018).

Carotenoids: Marine macroalgae are rich in carotenoids like lutein, violaxanthin, β-carotene, and fucoxanthin, which have significant bioactivity and therapeutic potential (Aditi et al., 2025). These carotenoids serve as essential photosynthetic pigments, providing distinctive colors and supporting photosynthesis. They also act as antioxidants, neutralizing harmful metabolic byproducts and promoting cellular health and longevity in the algae (Din et al., 2022). When included in aquatic animal diets, carotenoids enhance immune response, health, and feed palatability, improving overall nutrition (Mapelli-Brahm et al., 2023). The bioactive compounds in marine macroalgae have potential applications in aquaculture and human health (Senadheera et al., 2023). Fucoxanthin, a unique carotenoid in brown algae, offers powerful antioxidant properties due to its distinct molecular structure.

Fucoxanthin, a distinct type of carotenoid found specifically within marine brown seaweed, is a remarkable and critically significant photosynthetic pigment (Méresse et al., 2020). It has an intricate molecular structure, including an atypical allenic bond, a 5, 6-monoepoxide, and nine conjugated double bonds. The presence of the allenic bond within the intricate structural design of fucoxanthin significantly elevates its molecular reactivity, which, in turn, results in an enhancement of its exceptionally potent antioxidant properties, thereby establishing it as an invaluable compound across a multitude of biochemical applications (Zhang et al., 2015).

Marine bacteria: Marine bacterial species, including archaea and eubacteria, are increasingly studied as sources of novel compounds. Archaebacteria are abundant in soil, water, and hot springs, often feeding on organic waste, while eubacteria consist of bacteria and gram-positive actinomycetes (Debnath et al., 2007). Actinobacteria, used as probiotics in aquaculture, offer an environmentally friendly alternative to antibiotics by improving growth, water quality, gut microbiota, and pathogen protection. Actinomycetes are also valued in the pharmaceutical industry for producing immunoactive peptides, enzymes for food processing, and bioremediation, including pesticide breakdown, making aquaculture more sustainable (Oliveira et al., 2024). Despite the overuse of antibiotics, they remain crucial for treating aquatic disease outbreaks (James et al., 2023).

Bioactive substances derived from fish waste

Fish processing generates significant by-products, such as heads, tails, intestines, skin, blood, and bones, which make up about 52% of the total fish yield (Stevens et al., 2018). These materials are mainly repurposed into fish meal and fish oil. Fish meal, containing 70% protein, is a critical source of high-quality protein and is widely used in animal feed and fertilizer. Fish oil is applied in various industries, including soap production, glycerol extraction, and hydraulic oils (Ferraro et al., 2010). These by-products also contain bioactive compounds with substantial potential for diverse applications, further enhancing their value in both the food and industrial sectors. Furthermore, the bioactive substances that are extracted from fish by-products, along with their significant potential and typical applications, are discussed below.

Fish protein hydrolysate: Enzymatic hydrolysis of fish proteins produces fish protein hydrolysate (FPH), increasingly used in aquaculture feed (Chalamaiah et al., 2012; Suma et al., 2023). FPH offers improved digestibility and absorbability, with more soluble proteins than total protein (Irianto et al., 2018; Siddik et al., 2020). Short-chain peptides enhance feed palatability and efficiency, while antioxidant peptides protect fatty acids from peroxidation, promoting health and development (Chalamaiah et al., 2012; Siddik et al., 2018; Baraiya et al., 2024). FPH can replace fishmeal in fish feed and offers benefits like antihypertensive, antithrombotic, immunomodulatory, and antioxidative effects (Chalamaiah et al., 2012). A study showed FPH promoted shrimp growth when replacing fishmeal (Tejpal et al., 2021).

Chitin and chitosan: Chitosan, derived from chitin, is a biodegradable, non-toxic, and low-cost compound valued in sectors like food, cosmetics, and pharmaceuticals (Kim & Thomas, 2007; Wang et al., 2020). It's a polymer made from N-acetyl glucosamine, formed through the deacetylation of chitin, found in crustaceans and mollusks. Unlike other polysaccharides, chitosan has an alkaline or neutral pH (Leceta et al., 2013; Singh & Ray, 2000). Both chitin and chitosan improve fish performance, earning their classification as bioactive ingredients (Shahidi et al., 1999; Abdel-Ghany & Salem, 2020). Studies show that adding chitin or chitosan to the diets of species like tilapia, carp, mullet, trout, and loach enhances growth, feed conversion, and disease resistance (Abd El-Naby et al., 2020; Younus et al., 2020).

Derived from medicinal plants/ herbs

Medicinal plants, valued for their therapeutic properties, play a vital role in drug development and global healthcare systems, with two-thirds of the population relying on them for remedies (Rasool Hassan, 2012). They are preferred for their biocompatibility, cultural relevance, and fewer side effects. The use of medicinal plants in aquafeed has gained global interest, leading to extensive research (Li et al., 2019). Over 60 plant species, including *Allium sativum*, *Zingiber officinale*, and *Nigella sativa*, are recognized for their role in aquaculture. These plants offer an environmentally friendly and cost-effective alternative to synthetic hormones, antibiotics, and antioxidants in aquaculture (Hoseinifar et al., 2020), as mentioned in Table 1.

Derived from agricultural waste

There is huge amount of waste produced by the cultivation as well and processing of agricultural products. When it is making use of various parts like husks, seeds, roots, leaves, and stems to extract bioactive compounds, when waste material that were typically otherwise used (Table 2). The bioactive class of compounds comprises a variety of phenolic complexes, with flavonoids being the largest and most investigated group aside from coumarins, xanthones/ chalcones/stilbenes/lignin-type, which demonstrated effectiveness on many biological activities (Terpenoid class and carotenoidal moieties of essential oils are also gaining attention as potential benefits in addition to the traditional dietary fiber varieties like β-glucans or their related compounds (fructooligosaccharides, galacto-oligosaccharides) from branched-chain glucosinolin-related classes (Leyva-Lopez et al., 2020).

Table 1. Therapeutic potential of bioactive plant compounds in fish health

Sl No	Plant name	Bioactive compound	Effect	Fish	References
1.	Aloe vera	Aloe-emodin, aloin, aloesin, emodin, and acemannan	anti-inflammatory, antibacterial, antiseptic, anti-cancerous properties, anti-hypersensitivity, growth immune-modulatory effects, anti-mutagenic, anti-oxidant and gastro-intestinal promoting effects	Common carp	Mahdavi et al. (2013)
2.	Ashwagandha, *Withania somnifera*	Withaferin A, withanone, coumarin, kaempferol	anti-stress, anti-oxidant, rejuvenating, and immune modulatory	*L. rohita*	Sharma et al. (2017)
3.	Neem	Azadirachtin, nimbin, nimbidin, nimbolide, quercetin, and salannin	anti-inflammation, and anti-ulcer characteristic, antifungal, antimicrobial and antiparasitic	Asian sea bass and rainbow trout	Talpur and Ikhwanuddin (2013);Abidin et al. (2022)
4.	*Allium sativum*	Alliin, allicin, S-ally vinyldithiins, cystein, S-allymercaptocystein, ally propyl disulphide, ally trisulphide, ajoene,	antimicrobial, antiparasitic, antioxidant, and immunomodulatory properties.	*L. rohita*	Sahu et al. (2007)
5.	Honeysuckle	Chlorogenic acid, luteolin, loganin, isochlorogenic acids and various flavonoids	Growth promoter and anti-stress	*P. monodon*	Chen et al. (2013)
6.	*Ganoderma lucidum*	Ganoderic acids, ergosterol, ganoderenic acid A and D and ganoderenic acid A and D	Immunostimulant, anti-inflammatory, and anticancer properties and antitumor effects.	*C. carpio*	Chakrabarti (2005)
7.	*Eleutherococcusse nticosus*	Eleutherosides A-M, eleutherans, saponins, sesamins, syringin, beta sitosterol and chlorogenic acid	Growth performance immunostimulatory	*P. olivaceus*	Won et al. (2008)
8.	*Phylanthus niruri*	Rutin, quercetin, quercitrin, isoquercetrin, rhamnoside and ferulic acid	Growth performance immunostimulatory	*C. carpio*	Sunitha et al. (2017)
9.	*Clitoria ternatea*	Delphinidin, malvidin, kaempferol, quercetin, myricetin and cinnamic acid	Medicinal properties, anti- stress, antioxidant, hepatoprotective, antiviral, antibacterial, hypolipidemic and hypoglycemic	*O. niloticus*	Vidana Gamage et al. (2021)
10.	*Camellia sinensis*	Phenols, flavonoids and tannins	Immunomodulatory and resistance to bacterial disease	*L. rohita*	Debbarma et al. (2022)
11.	Dandelion (*Taraxacum officinale)*	Taraxerol, taraxasterol, taraxinic acid, β-glucopyranosyl ester, lupeol, luteolin, α -amyrin and β amyrin	Medicinal properties, anti-stress, antioxidant, antimicrobial and hepatoprotective activities	*L. rohita*	Tekam et al. (2024)

Table 2. Fish health benefits of bioactive compounds from agricultural by-products

Sl No	Plant waste	Compounds	Effect	Fish	Used	References
1.	Corn silk	Polyphenols and flavonoids	Immunostimulatory and antioxidative	Nile tilapia (*O. niloticus*)	Dietary supplements	Catap et al. (2015)
2.	Banana peel	Flavonoids, alkaloids, tannins, anthocyanins, glycosidesterpenoids and phlobatannins	Antibacterial, antihypertensive, antidiabetic, and anti-inflammatory effects	*L. rohita*	feed additive	Giri et al. (2016)
3.	Orange peel	Limonoids, enzymes, dietary fibers, carotenoids, and phenolic compounds	Health advantages, like, prevention of chronic diseases, the reduction of cancer incidence, and anti-inflammatory actions	Nile tilapia (*O. niloticus*)	Dietary supplements	Salem and Abdel-Ghany (2018)
4.	Grape seed	Carotenoids, phytosterols, phenolic acids, tocotrienols, and tocopherols	Improve growth performance, antioxidant status, and disease resistance	Common carp supplements	Dietary	Mehrinakhi et al. (2021)
5.	Olive waste cake	Polyphenols, flavanols and flavonoids	Antioxidant and anti-inflammatory properties	Rainbow trout (*Oncorhynchus mykiss*)	Dietary supplements	Hoseinifar et al. (2020)
6.	Mushrooms stalk	Lectins, polysaccharides (β-glucans), polysaccharide peptides, polysaccharide-protein complexes, lanostanoids, other terpenoids, alkaloids, sterols	Antioxidant	Nile tilapia (*O. niloticus*)	Dietary supplements	Ahmed et al. (2017)
7.	Chestnut wood and olive mill wastewater extract mixture	Phenolic compounds	Immunostimulant	*Cyprinus carpio* L.	Dietary supplements	Jahazi et al. (2020)
8.	Sorghum distillery residue	Phenolic compounds	Antioxidant	*Mugil cephalus*	Dietary supplements	Lee et al. (2009)

The biological characteristics and mechanism of action of bioactive substances

Antioxidant activity: Free radicals are highly reactive molecules with unpaired electrons, making them unstable and capable of damaging biomolecules like carbohydrates, proteins, lipids, and nucleic acids (Fernandes et al., 2018). They are byproducts of cellular metabolism, including the hydroperoxyl radical (HO_2^-), superoxide anion (O_2^-), and hydroxyl radical (OH^-) (Ayala et al., 2014; Mule et al., 2024). Excessive free radicals can damage lipids, proteins, and nucleic acids, with lipid peroxidation amplifying this damage and

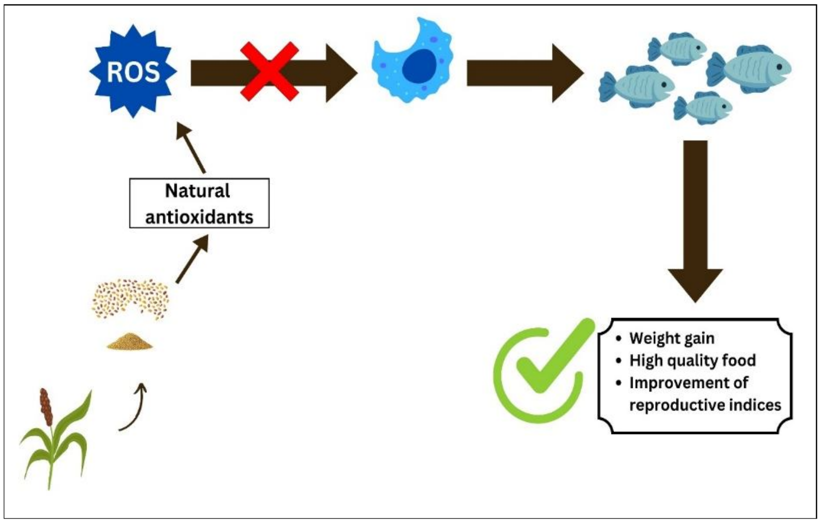

Fig. 3. Effect of natural antioxidants from bioactive compounds on mitigating oxidative stress and enhancing fish health and growth performance

generating harmful aldehydes, such as malondialdehyde (MDA) and 4-hydroxy-2-nonenal (HNE), which are cytotoxic and mutagenic (Pillon et al., 2012). Antioxidants counteract the harmful effects of free radicals by donating electrons or modulating transcription factors like NF-κB and NRF2. These factors regulate detoxifying and antioxidant enzymes such as catalase, superoxide dismutase, and glutathione peroxidase, which help fish to fight against pathogens, gain weight, and improve reproductive stress (Fig. 3) (Kim & Ki, 2017).

Immunostimulant activity: Immunostimulants, which often referred to as adjuvants or immunomodulators within academic research, represent a broad and diverse array of compounds or substances that play a significant role in enhancing the overall effectiveness and functionality of the immune system, ultimately leading to an increase in the resilience and defensive capabilities of various organisms when confronted with pathogenic agents (Vallejos-Vidal et al., 2016). These immunostimulants can be derived from a multitude of sources, encompassing a wide range of biological materials that include animal, plant, and bacterial origins, in addition to algae, nutritional constituents, hormones, or the various cytokines that are pivotal in mediating immune responses (Caipang & Lazado, 2015).

The most often assessed indicators for determining a substance's immunostimulant impact

The increase in the enzymatic effectiveness of lysozyme and myeloperoxidase (MPO) is substantial. Lysozyme manifests its antimicrobial properties by inducing the lysis of peptidoglycans, which are critical constituents of the cell wall in Gram-positive bacteria (Syngai & Ahmed, 2019), while MPO aids in the production of hypobromous, hypochlorous, and hypothiocyanite acids (Aratani, 2018).

An augmentation in the quantity of both erythrocytes and leukocytes is observed. The quantification of these cellular constituents serves as a pivotal metric for assessing the implications of various potential immunostimulants on the physiological well-being of organisms. A decline in the erythrocyte count denotes that the administered substance may be inflicting inadvertent harm (anemia) within the organism. Conversely, an elevation in the leukocyte population signifies an amplified immunological response to a prospective pathogenic agent. Additional hematological indicators encompass neutrophil count, hematocrit levels, and hemoglobin concentration, among others (Vallejos-Vidal et al., 2016).

Immunological parameters include complement components, which aid in signalling, opsonization, and microbial clearance (Chen et al., 2010), and immunoglobulin levels (Vallejos-Vidal et al., 2016). Melano macrophage centres (MMCs) and cytokines like interleukin-1 (IL-1), IL-6, and interferon-gamma (IFN-γ) are also key immune response indicators in fish (Agius & Roberts, 2003).

Modulation of the intestinal microbiota

The modification of the intestinal microbiome can be achieved through prebiotics, probiotics, and synbiotics (Ringø et al., 2016). Prebiotics, non-digestible components that influence microbiota composition, provide beneficial effects on the host after microbial fermentation (Tomás-Barberán et al., 2016). The goal is to enhance beneficial bacterial populations while suppressing harmful ones by selecting dietary additives that promote such changes. β-glucans, known for their immunomodulatory effects, influence microbiota composition depending on factors such as branching pattern, solubility, molecular weight, and structure (Volman et al., 2008). Soluble β-glucans, fermented by gut microbiota like bifidobacteria and lactobacilli, produce short-chain fatty acids (acetic, propionic, butyric acids), supporting microbiota balance and contributing to maintaining a healthy gut ecosystem (Maheshwari et al., 2019).

Conclusion

In conclusion, the integration of bioactive compounds into aquaculture practices offers a promising strategy for enhancing sustainability, improving product quality, and addressing the broader challenges associated with global food security. Utilizing natural substances such as antioxidants and antimicrobials, derived from fish processing by-products and medicinal plants, can significantly reduce reliance on synthetic antibiotics, while promoting the health, resilience, and adaptability of cultured aquatic species. This bio-based approach represents a pivotal advancement toward eco-efficient production systems and long-term sectoral success. Importantly, the application of these compounds should be viewed not as a temporary intervention, but as a dynamic and evolving strategy central to the development of a more sustainable and robust aquaculture sector and food supply chain.

Conflict of interest: The authors declare that they do not have any conflict of interest.

Author's contribution: IT: Writing of main draft; SS: Writing of main draft and editing; AA: Conceptualization, supervision, writing and reviewing of original draft; CD: Preparation of figures and tables; ND: Reviewing and editing; MKT: Literature collection and reviewing; DC: Reviewing and editing; SKP: Reviewing of manuscript; SKU: Reviewing of manuscript; MSA: Final editing and correction of manuscript.

Data availability statement: The corresponding author is willing to provide the raw data upon reasonable request.

Ethical approval: Not applicable.

Use of artificial intelligence tools: During the preparation of this work, the author(s) used ChatGPT to check the grammar. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

REFERENCES

Abd El-Naby, A. S., Al-Sagheer, A. A., Negm, S. S., & Naiel, M. A. (2020). Dietary combination of chitosan nanoparticle and thymol affects feed utilization, digestive enzymes, antioxidant status, and intestinal morphology of *Oreochromis niloticus*. *Aquaculture*, *515*, 734577. https://doi.org/10.1016/j.aquaculture.2019.734577

Abdel Ghany, H. M., & Salem, M. E. S. (2020). Effects of dietary chitosan supplementation on farmed fish; A review. *Reviews in Aquaculture*, *12*(1), 438-452. https://doi.org/10.1111/raq.12326

Abidin, Z. U., Hassan, H. U., Masood, Z., Rafique, N., Paray, B. A., Gabol, K., Shah, M. I. A., Gulnaz, A., Ullah, A., Zulfiqar, T., & Siddique, M. A. M. (2022). Effect of dietary supplementation of neem, *Azadirachta indica* leaf extracts on enhancing the growth performance, chemical composition and survival of rainbow trout, *Oncorhynchus mykiss*. *Saudi Journal of Biological Sciences*, *29*(4), 3075-3081. https://doi.org/10.1016/j.sjbs.2022.01.046

Aditi, Bhardwaj, R., Yadav, A., Swapnil, P., & Meena, M. (2025). Characterization of microalgal β-carotene and astaxanthin: exploring their health-promoting properties under the effect of salinity and light intensity. *Biotechnology for Biofuels and Bioproducts*, *18*(1), 18. https://doi.org/10.1186/s13068-025-02612-x

Agius, C., & Roberts, R. J. (2003). Melano macrophage centres and their role in fish pathology. *Journal of Fish Diseases*, *26*(9), 499-509. https://doi.org/10.1046/j.1365-2761.2003.00485.x

Ahmed, M., Abdullah, N., Shuib, A. S., & Razak, S. A. (2017). Influence of raw polysaccharide extract from mushroom stalk waste on growth and pH perturbation induced-stress in Nile tilapia, *Oreochromis niloticus*. *Aquaculture*, *468*, 60-70. https://doi.org/10.1016/j.aquaculture.2016.09.043

Anthes, C., & De Schutter, O. (2018). The Food and Agriculture Organization of the United Nations: Advancing the right to food to promote public health. In: B. M. Meier, & L. O. Gostin (Eds.) *Human Rights in Global Health: Rights-Based Governance for a Globalizing World* (pp.261-280), Oxford Academic. https://doi.org/10.1093/oso/9780190672676.003.0013

Aratani, Y. (2018). Myeloperoxidase: Its role for host defense, inflammation, and neutrophil function. *Archives of Biochemistry and Biophysics*, *640*, 47-52. https://doi.org/10.1016/j.abb.2018.01.004

Ayala, A., Muñoz, M. F., & Argüelles, S. (2014). Lipid peroxidation: production, metabolism, and signaling mechanisms of malondialdehyde and 4 hydroxy 2 nonenal. *Oxidative Medicine and Cellular Longevity*, *2014*(1), 360438. https://doi.org/10.1155/2014/360438

Baraiya, R., Anandan, R., Elavarasan, K., Prakash, P., Rathod, S. K., Rajasree, S. R., & Renuka, V. (2024). Potential of fish bioactive peptides for the prevention of global pandemic non-communicable disease: production, purification, identification, and health benefits. *Discover Food*, *4*(1), 34. https://doi.org/10.1007/s44187-024-00097-5

Boland, M. J., Rae, A. N., Vereijken, J. M., Meuwissen, M. P., Fischer, A. R., van Boekel, M. A., Rutherfurd, S. M., Gruppen, G., Moughan, P. J., & Hendriks, W. H. (2013). The future supply of animal-derived protein for human consumption. *Trends in Food Science & Technology*, *29*(1), 62-73. https://doi.org/10.1016/j.tifs.2012.07.002

Bondad-Reantaso, M. G., MacKinnon, B., Karunasagar, I., Fridman, S., Alday-Sanz, V., Brun, E., Groumellec, M., Li, A., Surachetpong, W., Karunasagar, I., Hao, B., Dall'Occo, A., Urbani, R., & Caputo, A. (2023). Review of alternatives to antibiotic use in aquaculture. *Reviews in Aquaculture*, *15*(4), 1421-1451. https://doi.org/10.1111/raq.12786

Caipang, C. M. A., & Lazado, C. C. (2015). Nutritional impacts on fish mucosa: immunostimulants, pre-and probiotics. In: *Mucosal Health in Aquaculture* (pp. 211-272). Academic Press. https://doi.org/10.1016/B978-0-12-417186-2.00009-1

Catap, E. S., Jimenez, M. R. R., & Tumbali, M. P. B. (2015). Immunostimulatory and anti-oxidative properties of corn silk from *Zea mays* L. in Nile tilapia, *Oreochromis niloticus*. *International Journal of Fisheries and Aquaculture*, *7*(3), 30-36. https://doi.org/10.5897/IJFA14.0449

Chakrabarti, R. (2005). Stimulation of immunity in Indian major carp *Catla catla* with herbal feed ingredients. *Fish & Shellfish Immunology*, *18*(4), 327-334. https://doi.org/10.1016/j.fsi.2004.08.005

Chalamaiah, M., Hemalatha, R., & Jyothirmayi, T. (2012). Fish protein hydrolysates: proximate composition, amino acid composition, antioxidant activities and applications: a review. *Food Chemistry*, *135*(4), 3020-3038. https://doi.org/10.1016/j.foodchem.2012.06.100

Chandini, S. K., Ganesan, P., & Bhaskar, N. (2008). *In vitro* antioxidant activities of three selected brown seaweeds of India. *Food Chemistry*, *107*(2), 707-713. https://doi.org/10.1016/j.foodchem.2007.08.081

Chavan, S. N., Ghughuskar, M. M., Meshram, S. J., Naik, S. D., Sawant, N. H., Prakash, P., Narsale, S. A., Gote, V. R., & Kondekar, S. S. (2024). Effect of different dietary protein levels on the growth, survival and changes in the hepatopancreatic cells of freshwater crab, *Barytelphusa cunicularis* (WESTWOOD 1836). *Journal of Experimental Zoology India*, *27*(1). https://doi.org/10.51470/jez.2024.27.1.1257

Chen, M., Daha, M. R., & Kallenberg, C. G. (2010). The complement system in systemic autoimmune disease. *Journal of Autoimmunity*, *34*(3), J276-J286. https://doi.org/10.1016/j.jaut.2009.11.014

Chen, X., Lin, H. Z., Jiang, S. G., Wu, K. C., Liu, Y. J., Tian, L. X., Zhang, Y. Q., & Niu, J. (2013). Dietary supplementation of honeysuckle improves the growth, survival and immunity of *Penaeus monodon*. *Fish & Shellfish Immunology*, *35*(1), 161-169. https://doi.org/10.1016/j.fsi.2013.04.020

Correia, R. T., Borges, K. C., Medeiros, M. F., & Genovese, M. I. (2012). Bioactive compounds and phenolic-linked functionality of powdered tropical fruit residues. *Food Science and Technology International*, *18*(6), 539-547. https://doi.org/10.1177/1082013211433077

Debbarma, S., Acharya, A., Mangang, Y. A., Monsang, S. J., Choudhury, T. G., Parhi, J., & Pandey, P. K. (2022). Immune-biochemical response and immune gene expression profiling of *Labeo rohita* fingerlings fed with ethanolic tea leaf extracts and its survivability against *Aeromonas hydrophila* infection. *Fish & Shellfish Immunology*, *130*, 520-529. https://doi.org/10.1016/j.fsi.2022.09.027

Debnath, M., Paul, A. K., & Bisen, P. S. (2007). Natural bioactive compounds and biotechnological potential of marine bacteria. *Current Pharmaceutical Biotechnology*, *8*(5), 253-260. https://doi.org/10.2174/138920107782109976

Din, N. A. S., Mohd Alayudin, A. S., Sofian-Seng, N. S., Rahman, H. A., Mohd Razali, N. S., Lim, S. J., & Wan Mustapha, W. A. (2022). Brown algae as functional food source of fucoxanthin: A review. *Foods*, *11*(15), 2235. https://doi.org/10.3390/foods11152235

FAO (Food and Agriculture Organization of the United Nations). (2024). *The State of World Fisheries and Aquaculture 2024 – Blue Transformation in action*. FAO, Rome. https://doi.org/10.4060/cd0683en

Fernandes, R. D. P. P., Trindade, M. A., & de Melo, M. P. (2018). Natural antioxidants and food applications: healthy perspectives. In: *Alternative and Replacement Foods* (pp. 31-64). Academic Press, London. https://doi.org/10.1016/B978-0-12-811446-9.00002-2

Ferraro, V., Cruz, I. B., Jorge, R. F., Malcata, F. X., Pintado, M. E., & Castro, P. M. (2010). Valorisation of natural extracts from marine source focused on marine by-products: A review. *Food Research International*, *43*(9), 2221-2233. https://doi.org/10.1016/j.foodres.2010.07.034

Food Security Information Network [FSIN]. (2024). *The Global Report on Food Crises 2024* [Report]. https://www.fsinplatform.org/grfc2024

Fraga, C. G., Galleano, M., Verstraeten, S. V., & Oteiza, P. I. (2010). Basic biochemical mechanisms behind the health benefits of polyphenols. *Molecular Aspects of Medicine*, *31*(6), 435-445. https://doi.org/10.1016/j.mam.2010.09.006

Giri, S. S., Jun, J. W., Sukumaran, V., & Park, S. C. (2016). Dietary administration of banana (*Musa acuminata*) peel flour affects the growth, antioxidant status, cytokine responses, and disease susceptibility of rohu, *Labeo rohita*. *Journal of Immunology Research*, *2016*(1), 4086591. https://doi.org/10.1155/2016/4086591

Hayes, M. (Ed.). (2012). *Marine Bioactive Compounds: Sources, Characterization and Applications*. Springer, Berlin.

Hoseinifar, S. H., Shakouri, M., Yousefi, S., Van Doan, H., Shafiei, S., Yousefi, M., Mazandarani, M., Torfi Mozanzadeh, M., Tulino, M. G., & Faggio, C. (2020). Humoral and skin mucosal immune parameters, intestinal immune related genes expression and antioxidant defense in rainbow trout (*Oncorhynchus mykiss*) fed olive (*Olea europea* L.) waste. *Fish & Shellfish Immunology*, *100*, 171-178. https://doi.org/10.1016/j.fsi.2020.02.067

Irianto, H. K., & Fawzya, Y. N. (2018). Fish protein hydrolysates: Their potential application for prevention of stunting. *Medical Research and Innovations*, *2*, 1-2.

Jahazi, M. A., Hoseinifar, S. H., Jafari, V., Hajimoradloo, A., Van Doan, H., & Paolucci, M. (2020). Dietary supplementation of polyphenols positively affects the innate immune response, oxidative status, and growth performance of common carp, *Cyprinus carpio* L. *Aquaculture*, *517*, 734709. https://doi.org/10.1016/j.aquaculture.2019.734709

James, G., Prasannan Geetha, P., Thavarool Puthiyedathu, S., & Vattringal Jayadradhan, R. K. (2023). Applications of Actinobacteria in aquaculture: prospects and challenges. *3 Biotech*, *13*(2), 42. https://doi.org/10.1007/s13205-023-03465-7

Kadam, S. U., Tiwari, B. K., Smyth, T. J., & O'Donnell, C. P. (2015). Optimization of ultrasound assisted extraction of bioactive components from brown seaweed *Ascophyllum nodosum* using response surface methodology. *Ultrasonics Sonochemistry*, *23*, 308-316. https://doi.org/10.1016/j.ultsonch.2014.10.007

Kim, K. M., & Ki, S. H. (2017). Nrf2: a key regulator of redox signaling in liver diseases. In: *Liver Pathophysiology* (pp. 355-374). Academic Press. https://doi.org/10.1016/B978-0-12-804274-8.00028-X

Kim, K. W., & Thomas, R. L. (2007). Antioxidative activity of chitosans with varying molecular weights. *Food Chemistry*, *101*(1), 308-313. https://doi.org/10.1016/j.foodchem.2006.01.038

Leceta, I., Guerrero, P., & De La Caba, V. K. (2013). Functional properties of chitosan-based films. *Carbohydrate Polymers*, *93*(1), 339-346. https://doi.org/10.1016/j.carbpol.2012.04.031

Lee, S. M., Cheng, H. L., & Pan, B. S. (2009). LDL oxidation, antioxidant capacity and growth of cultured grey mullet (*Mugil cephalus*) fed dietary sorghum distillery residue pretreated with polyethylene glycol. *Journal of Agricultural and Food Chemistry*, *57*(17), 7877-7882. https://doi.org/10.1021/jf901367u

Leicach, S. R., & Chludil, H. D. (2014). Plant secondary metabolites: Structure–activity relationships in human health prevention and treatment of common diseases. *Studies in Natural Products Chemistry*, *42*, 267-304. https://doi.org/10.1016/B978-0-444-63281-4.00009-4

Leyva-López, N., Lizárraga-Velázquez, C. E., Hernández, C., & Sánchez-Gutiérrez, E. Y. (2020). Exploitation of agro-industrial waste as potential source of bioactive compounds for aquaculture. *Foods*, *9*(7), 843. https://doi.org/10.3390/foods9070843

Li, M., Zhu, X., Tian, J., Liu, M., & Wang, G. (2019). Dietary flavonoids from *Allium mongolicum* Regel promotes growth, improves immune, antioxidant status, immune-related signaling molecules and disease resistance in juvenile northern snakehead fish (*Channa argus*). *Aquaculture*, *501*, 473-481. https://doi.org/10.1016/j.aquaculture.2018.12.011

Mahdavi, M., Hajimoradloo, A., & Ghorbani, R. (2013). Effect of Aloe vera extract on growth parameters of common carp (*Cyprinus carpio*). *World Journal of Medical Sciences*, *9*(1), 55-60. https://doi.org/10.5829/idosi.wjms.2013.9.1.75128

Maheshwari, G., Sowrirajan, S., & Joseph, B. (2019). β-Glucan, a dietary fiber in effective prevention of lifestyle diseases–An insight. *Bioactive Carbohydrates and Dietary Fibre*, *19*, 100187. https://doi.org/10.1016/j.bcdf.2019.100187

Mapelli-Brahm, P., Gómez-Villegas, P., Gonda, M. L., León-Vaz, A., León, R., Mildenberger, J., bours, C., Saravia, V., Vero, S., Vila, E., & Meléndez-Martínez, A. J. (2023). Microalgae, seaweeds and aquatic bacteria, archaea, and yeasts: Sources of carotenoids with potential antioxidant and anti-inflammatory health-promoting actions in the sustainability era. *Marine Drugs*, *21*(6), 340. https://doi.org/10.3390/md21060340

Mehrinakhi, Z., Ahmadifar, E., Sheikhzadeh, N., Moghadam, M. S., & Dawood, M. A. (2021). Extract of grape seed enhances the growth performance, humoral and mucosal immunity, and resistance of common carp (*Cyprinus carpio*) against *Aeromonas hydrophila*. *Annals of Animal Science*, *21*(1), 217-232. https://doi.org/10.2478/aoas-2020-0049

Méresse, S., Fodil, M., Fleury, F., & Chénais, B. (2020). Fucoxanthin, a marine-derived carotenoid from brown seaweeds and microalgae: A promising bioactive compound for cancer therapy. *International Journal of Molecular Sciences*, *21*(23), 9273. https://doi.org/10.3390/ijms21239273

Mule, S. R., Singh, D. K., Prakash, P., Narsale, S. A., Aklakur, M. D., Sardar, P., Biswas, G., Sahoo, S., Jayanta, M., & Mishra, S. (2024). Effect of dietary Anabaena supplementation on nutrient utilization, metabolism and oxidative stress response in *Catla catla* fingerlings. *Scientific Reports*, *14*(1), 27329. https://doi.org/10.1038/s41598-024-78234-4

Mutalipassi, M., Esposito, R., Ruocco, N., Viel, T., Costantini, M., & Zupo, V. (2021). Bioactive compounds of nutraceutical value from fishery and aquaculture discards. *Foods*, *10*(7), 1495. https://doi.org/10.3390/foods10071495

Naylor, R., Fang, S., & Fanzo, J. (2023). A global view of aquaculture policy. *Food Policy*, *116*, 102422. https://doi.org/10.1016/j.foodpol.2023.102422

Oliveira, L. R., Gonçalves, A. R., Quintela, E. D., Colognese, L., Cortes, M. V. D. C. B., & de Filippi, M. C. C. (2024). Genetic engineering of filamentous fungi: prospects for obtaining fourth-generation biological products. *Applied Microbiology*, *4*(2), 794-810. https://doi.org/10.3390/applmicrobiol4020055

Patekar, P., Lollen, K., Bhardwaj, A., & Munilkumar, S. (2025). Live food sourcing for ornamental fish farming and aquarium trade in India. In: A. K. Jain, A. J. Rane, & A. Sinha (Eds.) *Ornamental Fisheries and Aquarium Keeping* (1st ed., pp. 200-211). CRC Press, Boca Raton.

Pillon, N. J., Croze, M. L., Vella, R. E., Soulère, L., Lagarde, M., & Soulage, C. O. (2012). The lipid peroxidation by-product 4-hydroxy-2-nonenal (4-HNE) induces insulin resistance in skeletal muscle through both carbonyl and oxidative stress. *Endocrinology*, *153*(5), 2099-2111. https://doi.org/10.1210/en.2011-1957

Pradeepkiran, J. A. (2019). Aquaculture role in global food security with nutritional value: A review. *Translational Animal Science*, *3*(2), 903-910. https://doi.org/10.1093/tas/txz012

Prakash, P., Swapnil, N., Sheikh, S., Tekam, I., Bhalchandra, N., Madhav, G., & Munilkumar, S. (2023). Nutritional significance of fish in combating malnutrition. *International Journal of Environment and Climate Change*, *13*(11), 249-258. https://doi.org/10.9734/ijecc/2023/v13i113164

Rani, V., & Yadav, U. C. (Eds.). (2018). *Functional Food and Human Health* (pp. 698-698). Springer, Berlin.

Rasool Hassan, B. A. (2012). Medicinal plants (importance and uses). *Pharmaceutica Analytica Acta*, *3*(10), 2153-435. http://dx.doi.org/10.4172/2153-2435.1000e139

Ringø, E. Z. Z. V., Zhou, Z., Vecino, J. G., Wadsworth, S., Romero, J., Krogdahl, Å., Olsen, R. E., Dimitroglou, A., Foey, A., Davies, S., Owen, M., Lauzon, H. L., Martinsen, L. L., De Schryver, P., Bossier, P., Sperstad, S., & Merrifield, D. L. (2016). Effect of dietary components on the gut microbiota of aquatic animals. A never ending story?. *Aquaculture Nutrition*, *22*(2), 219-282. https://doi.org/10.1111/anu.12346

Routroy, S., Prakash, P., Kumar, R., Chandan, N. K., Sahu, B., Nanda, S., Pillai, B. R., & Mohanta, K. N. (2025). Effect of varied levels of dietary protein and lipid on growth response, nutrient utilization, and whole body composition of climbing perch, *Anabas testudineus* (Bloch, 1792) fry. *Aquaculture International*, *33*(1), 29. https://doi.org/10.1007/s10499-024-01677-z

Sahu, S., Das, B. K., Mishra, B. K., Pradhan, J., & Sarangi, N. (2007). Effect of *Allium sativum* on the immunity and survival of *Labeo rohita* infected with *Aeromonas hydrophila*. *Journal of Applied Ichthyology*, *23*(1), 80-86. https://doi.org/10.1111/j.1439-0426.2006.00785.x

Salem, M., & Abdel-Ghany, H. M. (2018). Effects of dietary orange peel on growth performance of Nile tilapia (*Oreochromis niloticus*) fingerlings. *Aquaculture Studies*, *18*(2), 127-134. https://doi.org/10.4194/2618-6381-v18_2_06

Senadheera, T. R., Hossain, A., & Shahidi, F. (2023). Marine bioactives and their application in the food industry: A review. *Applied Sciences*, *13*(21), 12088. https://doi.org/10.3390/app132112088

Shahidi, F., Arachchi, J. K. V., & Jeon, Y. J. (1999). Food applications of chitin and chitosans. *Trends in Food Science & Technology*, *10*(2), 37-51. https://doi.org/10.1016/S0924-2244(99)00017-5

Sharma, A., Chanu, T. I., & Deo, A. D. (2017). Dietary ashwagandha, *Withania somnifera* (L. dunal) potentiates growth, haemato-biochemical response and disease resistance of *Labeo rohita* (Hamilton, 1822) against *Aeromonas hydrophila* infection. *Journal of Entomology and Zoology Studies*, *5*(5), 1113-1119.

Siddik, M. A., Howieson, J., Partridge, G. J., Fotedar, R., & Gholipourkanani, H. (2018). Dietary tuna hydrolysate modulates growth performance, immune response, intestinal morphology and resistance to *Streptococcus iniae* in juvenile barramundi, *Lates calcarifer*. *Scientific Reports*, *8*(1), 15942. https://doi.org/10.1038/s41598-018-34182-4

Siddik, M. A., Howieson, J., Fotedar, R., & Partridge, G. J. (2021). Enzymatic fish protein hydrolysates in finfish aquaculture: A review. *Reviews in Aquaculture*, *13*(1), 406-430. https://doi.org/10.1111/raq.12481

Sigwart, J. D., Blasiak, R., Jaspars, M., Jouffray, J. B., & Tasdemir, D. (2021). Unlocking the potential of marine biodiscovery. *Natural Product Reports*, *38*(7), 1235-1242. https://doi.org/10.1039/D0NP00067A

Šimat, V., Elabed, N., Kulawik, P., Ceylan, Z., Jamroz, E., Yazgan, H., Čagalj, M., Regenstein, J. M., & Özogul, F. (2020). Recent advances in marine-based nutraceuticals and their health benefits. *Marine Drugs*, *18*(12), 627. https://doi.org/10.3390/md18120627

Singh, D. K., & Ray, A. R. (2000). Biomedical applications of chitin, chitosan, and their derivatives. *Journal of Macromolecular Science, Part C: Polymer Reviews*, *40*(1), 69-83. https://doi.org/10.1081/MC-100100579

Stevens, J. R., Newton, R. W., Tlusty, M., & Little, D. C. (2018). The rise of aquaculture by-products: Increasing food production, value, and sustainability through strategic utilisation. *Marine Policy*, *90*, 115-124. https://doi.org/10.1016/j.marpol.2017.12.027

Suma, A. Y., Nandi, S. K., Abdul Kari, Z., Goh, K. W., Wei, L. S., Tahiluddin, A. B., Seguin, P., Herault, M., Al Mamun, A., Téllez-Isaías, G., & Anamul Kabir, M. (2023). Beneficial effects of graded levels of fish protein hydrolysate (FPH) on the growth performance, blood biochemistry, liver and intestinal health, economics efficiency, and disease resistance to *Aeromonas hydrophila* of pabda (*Ompok pabda*) fingerling. *Fishes*, *8*(3), 147. https://doi.org/10.3390/fishes8030147

Sunitha, C., Mettilda, S., & Vinoliya, J. (2017). Effect of dietary intake of Phyllanthus niruri L. on fingerlings of freshwater fish, *Cyprinus carpio* L. *International Journal of Fisheries and Aquatic Studies*, *5*(1), 352-359.

Syngai, G. G., & Ahmed, G. (2019). Lysozyme: A natural antimicrobial enzyme of interest in food applications. In: *Enzymes in food biotechnology* (pp. 169-179). Academic Press. https://doi.org/10.1016/B978-0-12-813280-7.00011-6

Talpur, A. D., & Ikhwanuddin, M. (2013). *Azadirachta indica* (neem) leaf dietary effects on the immunity response and disease resistance of Asian seabass, *Lates calcarifer* challenged with *Vibrio harveyi*. *Fish & Shellfish Immunology*, *34*(1), 254-264. https://doi.org/10.1016/j.fsi.2012.11.003

Tejpal, C. S., Kumar, L. R., Elavarasan, K., Renuka, V., & Anas, K. K. (2022). Bioactive based feed formulation for aquaculture applications, *ICAR-CIFT*, 205-207.

Tejpal, C., Vijayagopal, P., Elavarasan, K., Prabu, D. L., Lekshmi, R., Anandan, R., Şanal, E., Asha, K., Chatterjee, N., Mathew, S., & Ravishankar, C. (2021). Evaluation of pepsin derived tilapia fish waste protein hydrolysate as a feed ingredient for silver pompano (*Trachinotus blochii*) fingerlings: Influence on growth, metabolism, immune and disease resistance. *Animal Feed Science and Technology*, *272*, 114748. https://doi.org/10.1016/j.anifeedsci.2020.114748

Tekam, I., Dubey, S., Mahajan, S., Sheikh, S., Singh, S. M., & Kewat, A. (2024). Quantitative and qualitative assessment of phytochemicals in dandelion (*Taraxacum officinale*) leaves. *Journal of Experimental Zoology India*, *27*(1). https://doi.org/10.51470/jez.2024.27.1.699

Tomás-Barberán, F. A., Selma, M. V., & Espín, J. C. (2016). Interactions of gut microbiota with dietary polyphenols and consequences to human health. *Current Opinion in Clinical Nutrition & Metabolic Care*, *19*(6), 471-476. https://doi.org/10.1097/MCO.0000000000000314

Vallejos-Vidal, E., Reyes-López, F., Teles, M., & MacKenzie, S. (2016). The response of fish to immunostimulant diets. *Fish & Shellfish Immunology*, *56*, 34-69. https://doi.org/10.1016/j.fsi.2016.06.028

Vidana Gamage, G. C., Lim, Y. Y., & Choo, W. S. (2021). Anthocyanins from *Clitoria ternatea* flower: Biosynthesis, extraction, stability, antioxidant activity, and applications. *Frontiers in Plant Science*, *12*, 792303. https://doi.org/10.3389/fpls.2021.792303

Volman, J. J., Ramakers, J. D., & Plat, J. (2008). Dietary modulation of immune function by β-glucans. *Physiology & Behavior*, *94*(2), 276-284. https://doi.org/10.1016/j.physbeh.2007.11.045

Von Grebmer, K., Bernstein, J., Wiemers, M., Reiner, L., Bachmeier, M., Hanano, A., Ní Chéilleachair, R., Foley, C., Sheehan, T., Gitter, S., Larocque, G., & Fritschel, H. (2023). *2023 Global Hunger Index*: *The Power of Youth in Shaping Food Systems*. Welthungerhilfe (WHH), Concern Worldwide, Dublin.

Wang, H., Rehman, K. U., Feng, W., Yang, D., Rehman, R. U., Cai, M., Zhang, J., Yu, Z., & Zheng, L. (2020). Physicochemical structure of chitin in the developing stages of black soldier fly. *International Journal of Biological Macromolecules*, *149*, 901-907. https://doi.org/10.1016/j.ijbiomac.2020.01.293

Won, K. M., Kim, P. K., Lee, S. H., & Park, S. I. (2008). Effect of the residuum extract of Siberian ginseng *Eleutherococcus senticosus* on non-specific immunity in olive flounder *Paralichthys olivaceus*. *Fisheries Science*, *74*(3), 635-641. https://doi.org/10.1111/j.1444-2906.2008.01568.x

Younus, N., Zuberi, A., Mahmoood, T., Akram, W., & Ahmad, M. (2020). Comparative effects of dietary micro-and nano-scale chitosan on the growth performance, non-specific immunity, and resistance of silver carp *Hypophthalmichthys molitrix* against *Staphylococcus aureus* infection. *Aquaculture International*, *28*(6), 2363-2378. https://doi.org/10.1007/s10499-020-00595-0

Zhang, H., Tang, Y., Zhang, Y., Zhang, S., Qu, J., Wang, X., Kong, R., Han, C., & Liu, Z. (2015). Fucoxanthin: A promising medicinal and nutritional ingredient. *Evidence Based Complementary and Alternative Medicine*, *2015*(1), 723515. https://doi.org/10.1155/2015/723515

Zhang, Y., Cai, P., Cheng, G., & Zhang, Y. (2022). A brief review of phenolic compounds identified from plants: Their extraction, analysis, and biological activity. *Natural Product Communications*, *17*(1), 1934578X211069721. https://doi.org/10.1177/1934578X211069721

Received - 27.05.2025, Accepted - 19.08.2025, Published - 17.09.2025 (Online), 01.12.2025 (Print)
Section Editor: Dr. Dibyendu Kamilya, Editorial Board Member