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Nourishing Aquatic Life: A Comprehensive Reviewing of Fish Feed Strategies and Disease Combat in Aquaculture

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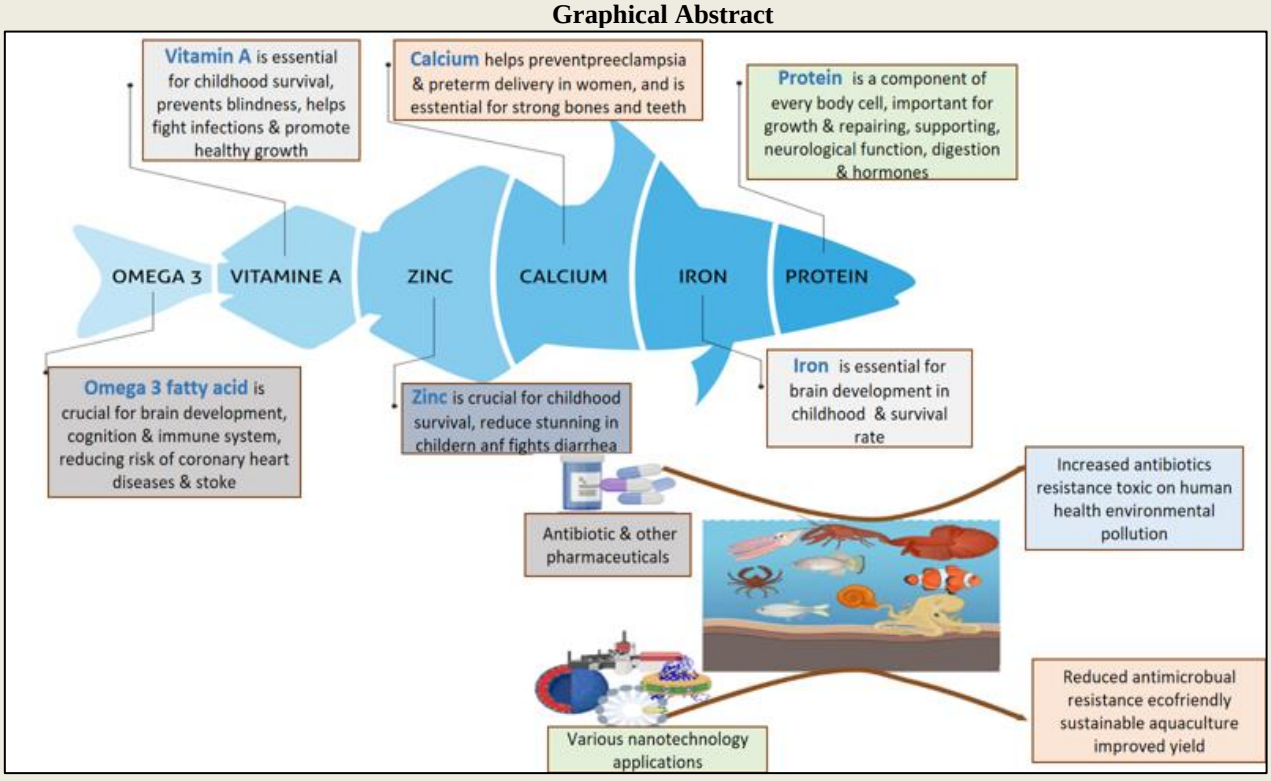
Abstract **Review Article**

Graphical Abstract



With an increasing focus on creating sustainable methods that satisfy the nutritional requirements of aquatic life while successfully containing disease outbreaks, aquaculture has emerged as a crucial element of global food security. Nourishing Aquatic Life: A Comprehensive Review of Fish Feed Strategies and Disease Combat in Aquaculture explores the delicate balance between disease management and feed optimization, two crucial factors influencing the ecological sustainability and productivity of aquaculture systems. Innovative substitutes, including plant-based proteins, insect meal, and microbial sources, are being assessed alongside conventional fish feed formulations, which rely on fishmeal and fish oil to lessen environmental stresses while preserving high nutritional value. This article also covers

how probiotics, prebiotics, and immunostimulants can improve fish immunity and resilience against common diseases, lowering the need for antibiotics and the likelihood of resistance. Additionally, we look at the most recent developments in fish feed formulation using biofloc, genetic engineering, and nanotechnology, emphasizing their implications for better fish health and disease resistance. These innovative strategies offer a hopeful vision for the future of aquaculture, inspiring us to continue our efforts in this field.

Keywords: Aquaculture nutrition, Disease prevention in aquaculture, Aquatic animal immunity, Fish feed formulation, Sustainable fish feed, Fish health management.

INTRODUCTION

Growing aquatic species in regulated settings, such as fish, shellfish, algae, and plants, is known as aquaculture, and it has become a vital part of the world's food security (Jennings *et al.,* 2016). The need for sustainable, high-protein food sources will only expand as the world's population rises. This need is satisfied by aquaculture, which offers a steady supply of seafood to support wild fisheries, which have been severely impacted by pollution, overfishing, and climate change (Clavelle *et al.,* 2019). Aquaculture produces almost half of the world's fish, and as sustainable aquaculture techniques improve, this percentage is predicted to rise. Beyond only making food, aquaculture plays a vital role in the economies of many nations, creating jobs and increasing income, particularly in rural and coastal regions. This socio-economic impact is a testament to the value of aquaculture. Additionally, it contributes significantly to the global diversification of diets by offering necessary nutrients for human health, such as omega-3 fatty acids (Shahidi *et al.,* 2016). The sector also promotes sustainable practices by creating low-impact farming methods, including recirculating systems, integrated multi-trophic aquaculture, and enhanced feed formulations to reduce environmental footprints. Aquaculture is thus positioned as an essential component of the future of food production and global nutrition, supporting food security while also aligning with global ecological goals (Gephart *et al.,* 2020).

Achieving sustainable fish production requires careful attention to feed quality and disease control. High-quality feed directly influences fish growth rates, reproductive success, and general health to ensure successful and profitable fish farming (Ochokwu *et al.,* 2015). In addition to providing the nutrients required for health and growth, optimal feed promotes effective nutrient absorption, which lowers waste and lessens its adverse effects on the environment. Since fish are susceptible to their surroundings, low-quality feed can introduce pollutants, weaken immunity, and cause toxic chemicals to build up in fish tissues, which might be dangerous for human consumption (Syanya *et al.,* 2023). Because poor nutrition can result in dietary deficits and stress, proper feed quality management also includes balancing protein, fats, vitamins, and minerals to meet species-specific requirements, making fish more prone to illness. Moreover, disease control is essential to preserving fish health and guaranteeing aquaculture systems' long-term viability (Dar *et al.,* 2020). Outbreaks of disease, which are frequently made worse by overcrowding, contaminated water, and malnutrition, can cause enormous financial losses, lower fish yields, and a greater need for medications, all of which can lead to antibiotic resistance. Regular health checks, immunizations, biosecurity protocols, and eco-friendly treatments are examples of sustainable disease management techniques that help lower disease transmission and increase fish resistance, which lowers death rates and boosts production efficiency (Seethalakshmi *et al.,* 2021). A balanced ecosystem in fish farming is produced by combining superior feed and efficient disease management, which results in healthier fish, less of an adverse influence on the environment, and more stable production systems that support international sustainability objectives. Aquaculture may achieve sustainable growth, protect food security, and maintain ecological balance in aquatic habitats by prioritizing proactive health management and adequate nutrition (Aly *et al.,* 2024).

By examining the role of biopsychosocial approaches in improving patient outcomes and addressing the mental health issues that frequently accompany long-term physical conditions, this review aims to provide a thorough examination of the relationship between managing chronic illnesses and psychological care (Moos *et al.,* 2000). By combining research from several fields, such as psychology, medicine, neuroscience, and integrative health, this review seeks to fill gaps in the current literature and provide a comprehensive understanding of how psychological interventions can support medical treatment in managing chronic illnesses. Some of the main goals are examining evidence-based techniques like biofeedback, mindfulness, and cognitive-behavioral therapy, as well as cutting-edge methods like teletherapy, AI-powered emotional health prediction models, and nature-based therapies (Gyaneshwar *et al.,* 2024). The primary purpose of this study encompasses both conventional and novel treatment approaches, emphasizing their effectiveness and capacity to adjust to changing healthcare systems, individual demands, and technology breakthroughs. This study attempts to address policy implications, identify opportunities for future research, and offer frameworks for implementing integrative psychological and medical treatment by critically analyzing these diverse methods. The review's ultimate goal is to emphasize the value of a

multidisciplinary approach in the management of chronic illnesses and to promote mental health concerns as a crucial part of efficient, long-lasting healthcare.

Current Trends in Fish Feed Formulation

Significant advancements in fish feed composition have occurred recently, mainly due to aquaculture's desire for economical and sustainable solutions (Boyd *et al.,* 2020). Because of their high nutritional value and ease of digestion, fishmeal and fish oil have historically been the primary protein sources in fish feed. Researchers and manufacturers are now looking for alternative protein sources, such as plant-based proteins (such as soy, wheat, and pea proteins), insect meal, and algae, due to the decline of wild fish supplies and the growing price of components produced from fish. Although plant-based proteins are inexpensive and widely accessible, they frequently lack critical amino acids and include anti-nutritional elements that might impair fish growth. Algae offer vital amino acids and advantageous bioactive chemicals that enhance fish health and immunity. In contrast, insect meal, which is high in protein and omega-3 fatty acids, has shown promise since it resembles the natural diet of many fish species. In addition to proteins, vital elements, including lipids, vitamins, and minerals, are essential for fostering healthy development, robust immune systems, and resistance to disease in various fish species. However, creating nutritionally balanced diets may be difficult, mainly because various aquaculture species have varying dietary requirements (Hixson *et al.,* 2014). For instance, omnivore or herbivorous fish may react differently to specific food sources, whereas carnivorous fish have more significant protein needs. Additionally, concerns, including digestibility, palatability, and nutrient stability during feed preparation and storage, need to be adequately controlled. Aquaculture nutrition research continues to prioritize developing ideal formulations that satisfy the unique requirements of each species while being both economically and ecologically viable (Lal *et al.,* 2024).

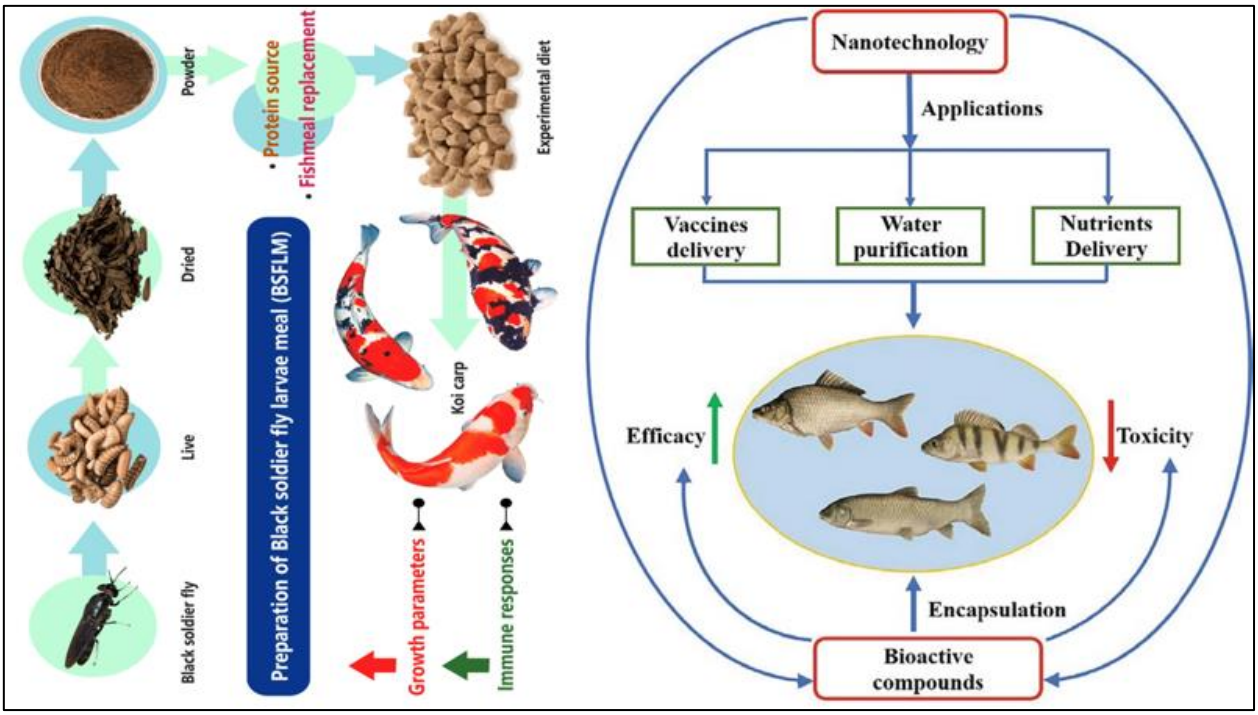


Fig 1: Fish Feed Formulation

Table 1: Conventional and Alternative Fish Feed Components

Feed Component	Conventional Source	Alternative Source	Nutritional Profile	Benefits	Challenges	Species Suitability
Protein	Fishmeal	Plant proteins (soy, wheat, pea)	Essential amino acids; higher in fishmeal	Essential for growth, development, and muscle mass	Plant proteins may lack some amino acids	Fishmeal is preferred for carnivorous species
		Insect meal (black soldier fly larvae)	High in essential amino acids and digestible protein	Mimics natural diet; sustainable	Production scale and cost limitations	Suitable for omnivorous and carnivorous species

		Algae (Spirulina, Chlorella)	Balanced amino acids and bioactive compounds	Supports immunity and pigmentation	It may be costly in large quantities	Suitable for all species
Lipids	Fish oil	Algal oil, vegetable oils	Omega-3 and Omega-6 fatty acids	Supports brain, heart health, and immunity	The balance of fatty acids in alternatives is variable	Algal oil suitable for high Omega-3 demand
		Insect oil	Contains fatty acids similar to fish oil	Sustainable can enhance feed palatability	Limited large-scale production	Promising for omnivores
Vitamins & Minerals	Synthetic vitamins/minerals	Plant-based vitamins, algae-derived	Supports immunity, metabolism, and bone health	Essential for various biological functions	Bioavailability varies among sources	Essential for all species
Carbohy-drates	Corn, wheat, and other grains	Cassava, seaweed extracts	Source of energy	Inexpensive, easy to digest for omnivores	Carnivorous fish have limited carbohydrate tolerance	Suitable for omnivorous species
Immunostimulants	Synthetic supplements	Herbal extracts, probiotics	Enhance immune response and disease resistance	Natural and may reduce disease risks	Inconsistent efficacy across different species	Effective in various species, depending on strains
Pigments	Synthetic carotenoids	Algae, shrimp meal	Carotenoids for skin and flesh coloration	Enhances appearance and marketability	Cost and sustainability of natural pigments	Used in ornamental and salmonid species
Binders and Stabilizers	Gelatin, synthetic binders	Seaweed extracts (e.g., agar, carrageenan)	Improves pellet stability and durability	Better for water quality and feed efficiency	Some may alter nutrient bioavailability	Required for all pelletized feeds

Feed Strategies and Nutrient Optimization

With an emphasis on providing balanced meals catered to the requirements of every species, feed strategies, and nutrient optimization are crucial elements in optimizing animal health, development, and production (Vlaicu *et al.,* 2023). Each species has different nutritional needs, which are impacted by environmental circumstances, development stage, and reproductive cycle. Animals need a balanced diet of proteins, carbs, fats, vitamins, and minerals for healthy development, reproduction, and general well-being. Applying specific methodologies that consider an animal's distinct digestive system, metabolic rate, and capacity for nutrient absorption is necessary for precision in feed composition. For instance, feed formulations are modified in aquaculture to guarantee that each species obtains the proper amino acid profile since species such as salmon and tilapia have varying protein requirements. Feed additives like probiotics, prebiotics, and enzymes are frequently used in balanced diet formulations because they improve gut health and nutrient absorption, increasing feed efficiency (Upadhayay *et al.,* 2014). Prebiotics, indigestible fibers, act as food for probiotics, which are good living microorganisms that aid digestion and absorption of nutrients and help maintain a healthy microbial balance in the gut. In order to make complicated nutrients more accessible to digest, enzymes are given to feeds. This is especially helpful for diets that contain a lot of fiber or plant-based substances. Feed strategies significantly emphasize sustainable animal production since these additions optimize nutrients, promote immunological function, minimize feed waste, and improve overall growth rates (Bashir *et al.,* 2024).

Environmental Impact of Fish Feeds and Eco-Friendly Alternatives

Due in significant part to the usage of fishmeal and fish oil from wild fish, which strain marine ecosystems and fuel overfishing, traditional fish feeds have a substantial adverse environmental impact (Spalvins *et al.,* 2018). Furthermore, conventional diets can include high levels of phosphate and nitrogen, which fish excrete as nutrient-rich wastewater effluents. These nutrients can infiltrate nearby aquatic environments, leading to eutrophication and toxic algal blooms that lower oxygen levels and endanger marine biodiversity. Several feed techniques are being developed to lower emissions of phosphorus and nitrogen in order to counteract these consequences. To maximize the nutritional intake of fish, for example, feed formulation modifications and precision feeding techniques are employed to ensure that the fish absorb more of the meal and excrete less. Plant-based diets and organic feeds are examples of promising sustainable feed substitutes

(Alcorta *et al.*, 2021). Organic feeds promote ecosystem health and might lessen nutrient contamination since they lack chemical pollutants and artificial additions. To lessen the need to exploit wild fish supplies, plant-based diets that include substances like soy, algae, and other agricultural wastes are being investigated more and more as alternatives to fishmeal and fish oil. Case studies from aquaculture enterprises worldwide demonstrate successful implementation of environmentally friendly feed techniques. By using insect-based feed, which uses larvae fed on organic waste, a salmon farm in Norway, for instance, drastically decreased its environmental impact and adopted a circular economy approach to feeding. Another illustration is a tilapia farm in Asia that switched to plant-based diets, improving local water quality and reducing nitrogen runoff by 30%. These creative methods show how sustainable feed options may support the expansion of the aquaculture sector while preserving aquatic habitats (Muhammad *et al.*, 2024).

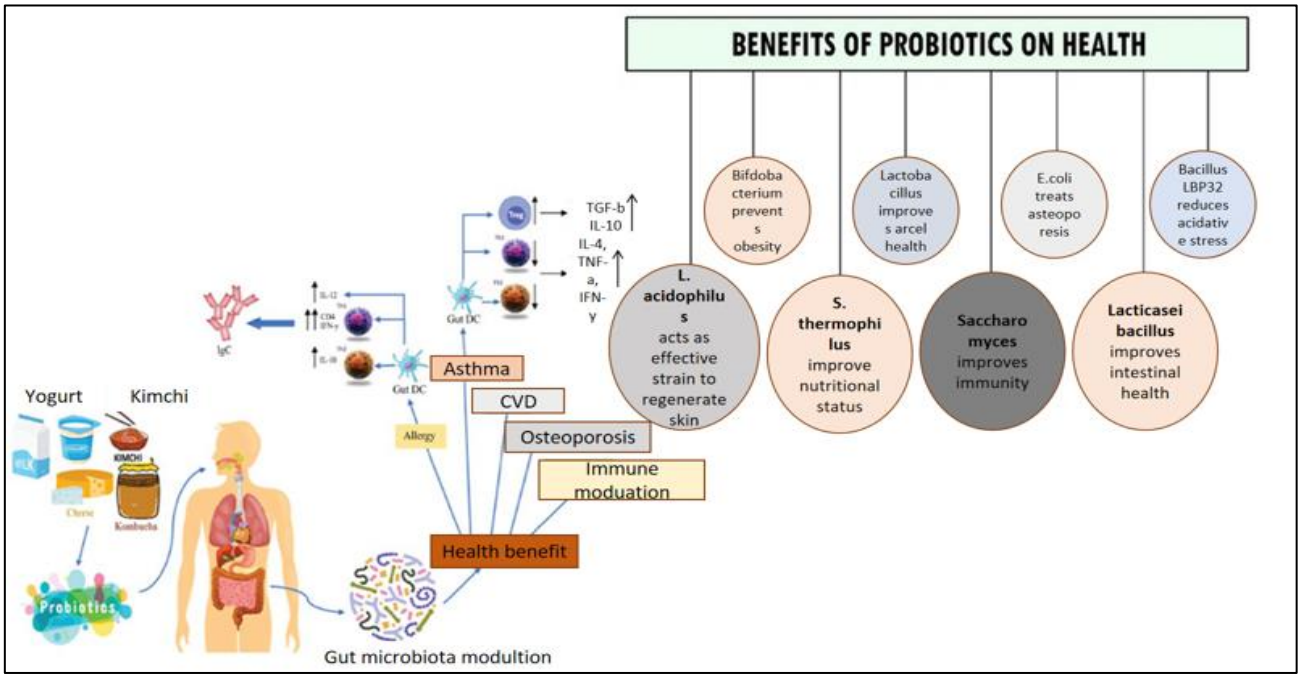


Fig 2: Feed Strategies and Nutrient Optimization

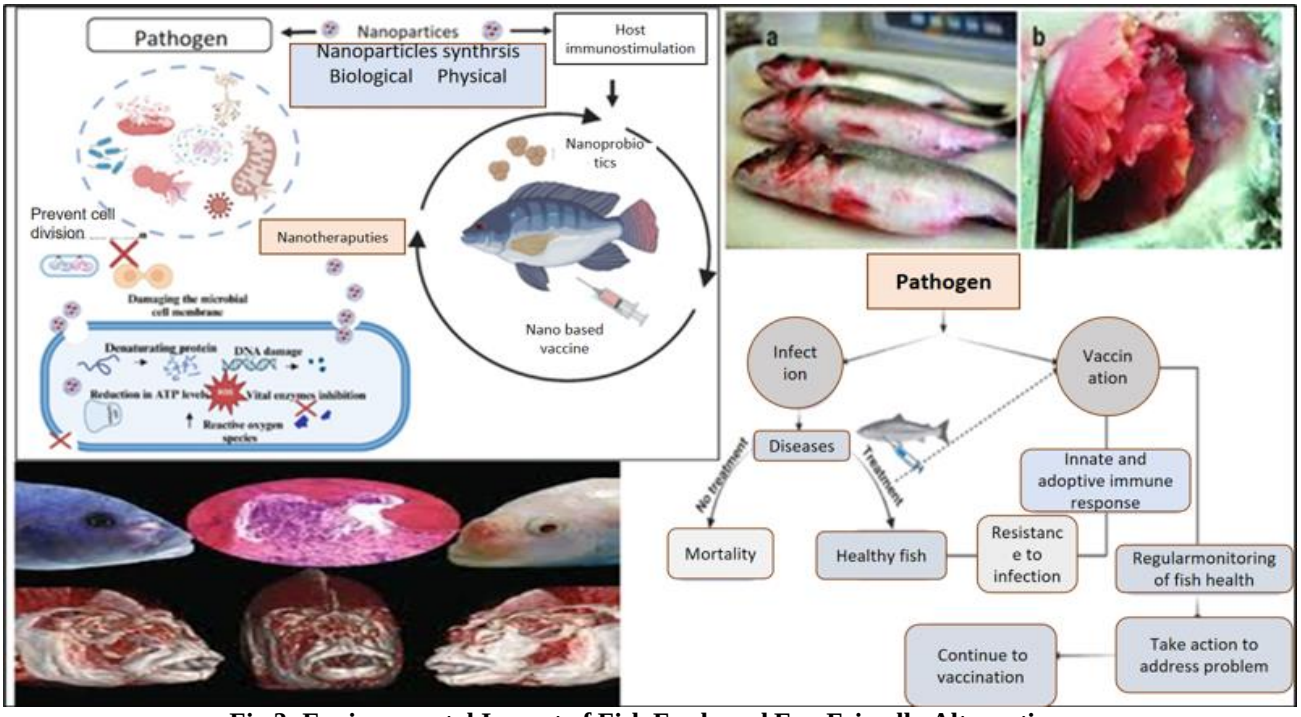


Fig 3: Environmental Impact of Fish Feeds and Eco-Friendly Alternatives

Fish Immunity and Disease Management in Aquaculture

In aquaculture, maintaining fish health and production in the face of frequent bacterial, viral, fungal, and parasitic diseases depends on fish immunity and disease control. Aquaculture operations can be severely damaged by diseases like bacterial infections (like Aeromonas and Vibrio), viral infections (like infectious pancreatic necrosis virus), fungal diseases (like saprolegniosis), and parasitic infestations (like Ichthyophthirius multifiliis, or "ich"). Fish need a complex immune system that includes innate and adaptive responses to fight these illnesses (Baig *et al.*, 2024). The initial line of defense is the innate immune system, which includes cellular reactions that generate antimicrobial peptides and activate immune cells like neutrophils and macrophages to combat infections and physical barriers like the skin and mucus (Abbas *et al.*,2024). Despite being less developed than humans, fish's adaptive immune system is essential for long-term protection. It develops a "memory" of infections, allowing for quicker and stronger reactions when re-exposed. A comprehensive strategy is needed to improve fish immunity and disease resistance, with a balanced diet playing a key role. While probiotics and prebiotics can further enhance gut health and pathogen resistance, essential nutrients like vitamins (C and E), minerals (such as zinc and selenium), and omega-3 fatty acids are essential for strengthening immune systems. Maintaining healthy populations and reducing disease outbreaks in fish farming requires the integration of vaccination, effective husbandry techniques, and stress management (Assefa *et al.*, 2018).

Table 2: Fish Immunity and Disease Management in Aquaculture

Disease Type	Common Diseases	Pathogens	Affected Species	Symptoms	Preventive Strategies
Bacterial Infections	*Aeromonas* infections (e.g., motile aeromonad septicemia), *Vibrio* infections (e.g., vibriosis), *Edwardsiella* infections	*Aeromonas hydrophila*, *Vibrio anguillarum*, *Edwardsiella tarda*	Tilapia, catfish, salmonids, eels	Hemorrhagic lesions, ulcers, septicemia	Vaccination, water quality management, stress reduction, antibiotics (with caution), probiotics, proper nutrition
Viral Infections	Infectious pancreatic necrosis, viral hemorrhagic septicemia, koi herpesvirus	Infectious pancreatic necrosis virus (IPNV), viral hemorrhagic septicemia virus (VHSV), koi herpesvirus (KHV)	Salmonids, koi, common carp	Swelling, pale gills, lethargy, high mortality	Vaccination, biosecurity measures, disinfection, quarantine, good husbandry practices, maintaining low stocking density
Fungal Infections	Saprolegniosis, ichthyophoniasis	*Saprolegnia* spp., *Ichthyophonus* spp.	Various freshwater and marine fish	Cottony white growths, tissue necrosis	Good water quality, anti-fungal treatments, removal of infected fish, proper handling, avoiding skin abrasions
Parasitic Infections	White spot disease (Ich), gill flukes, skin flukes	*Ichthyophthirius multifiliis*, *Dactylogyrus* spp., *Gyrodactylus* spp.	Freshwater fish (Ich), marine fish	White spots on skin, gill damage, lethargy	UV sterilization, salt baths, anti-parasitic treatments, maintaining low-stress environments
Nutritional Deficiency-Related Immunosuppression	It is not a specific disease, but poor nutrition can lower infection resistance.	*Ichthyophthirius multifiliis*, *Dactylogyrus* spp., *Gyrodactylus* spp.	All aquaculture species	Increased susceptibility to disease, poor growth	A balanced diet with essential vitamins, minerals, omega-3 fatty acids, probiotics, prebiotics

Disease Prevention through Nutritional Interventions

Through targeted nutrient supplementation, nutritional treatments are crucial for improving immune responses and general health, which is crucial for disease prevention across species (Kiron *et al.*, 2012). Vitamins and minerals, including vitamins C, E, and selenium, are essential antioxidants that counteract free radicals and prevent cellular damage. These nutrients greatly lessen

oxidative stress in fish, which might otherwise impair immunity and increase disease susceptibility. For example, vitamins E and C act in concert to stabilize cell membranes and prevent lipid peroxidation. In contrast, vitamin C plays a key role in collagen formation, wound healing, and immune system strengthening. Glutathione peroxidase, an enzyme essential for detoxifying peroxides and preserving redox equilibrium inside cells, requires selenium, a trace element, as a cofactor. Furthermore, extracts from plants and herbs, such as echinacea, turmeric, and garlic, have immunomodulatory qualities that promote disease resistance (Tiwari *et al.*, 2018). These natural extracts offer antibacterial properties that guard against infections, boost antibody synthesis, and activate immune cells. The relevance of balanced nutrition in aquaculture and fisheries management as a sustainable strategy for disease prevention is highlighted by the addition of these antioxidants and immunomodulatory agents to fish diets, which increases the fish's resistance to infections and enhances their general health (Naseer *et al.*, 2024).

Technological Advances in Disease Control

Aquaculture disease control has been transformed by technological advancements, which have also produced new techniques to enhance aquatic species' sustainability, development, and health (Nasr-Eldahan *et al.*, 2021). Originally developed as a tool for human and animal health, vaccines are now used in aquaculture, where they are essential for avoiding infections and lowering the need for antibiotics. Oral vaccines and immersion methods are two examples of vaccine delivery innovations that have made it easier to apply them in aquaculture. This has improved disease resistance in populations by enabling the efficient and effective immunization of many fish. Significant advancements in aquaculture feeding and disease control are also being made possible by nanotechnology. By directly delivering nutrients, antibiotics, and other advantageous substances to specific cells or tissues, nanoscale carriers might increase the bioavailability and efficacy of these therapies while reducing trash and its effects on the environment (Harish *et al.*, 2022). Additionally, the creation of vaccines based on nanoparticles that enhance immune responses at lower dosages is made possible by this precision-targeted delivery. Additionally, advances in biosensors, PCR (polymerase chain reaction) tests, and portable imaging devices, which may quickly identify pathogens at the earliest stages of infection, have advanced diagnostic tools for early illness identification. In addition to preventing epidemics, early diagnosis allows for prompt actions, maintaining stock health, and raising overall production. These technical developments are changing aquaculture by creating better aquatic conditions, lowering the occurrence of illness, and encouraging more effective, sustainable practices (Diana *et al.*, 2013).

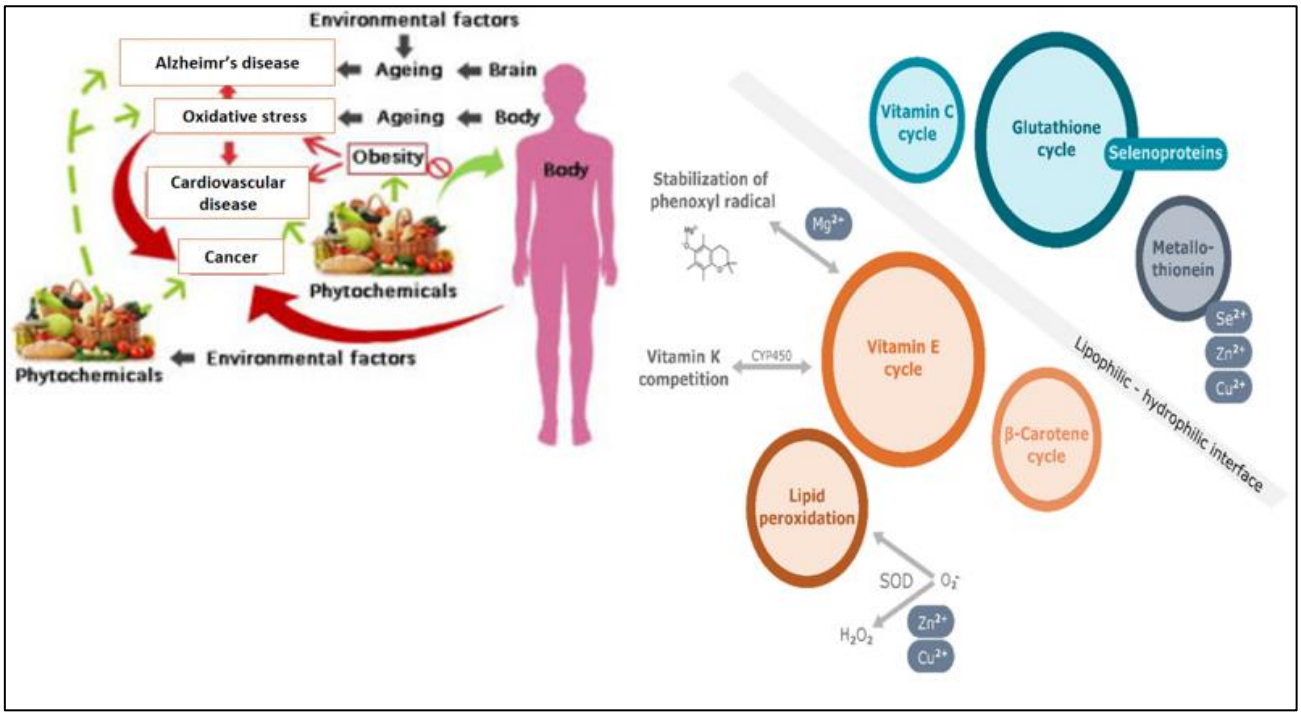


Fig 4: Technological Advances in Disease Control

Integrated Approaches Combining Nutrition and Disease Management

In order to support robust and sustainable aquatic systems, integrated techniques in aquaculture place an increasing emphasis on integrating feeding, disease management, and pest control (Zajdband *et al.*, 2011). Aquaculture operations may improve fish health and production efficiency while lowering their dependency on chemicals and antibiotics by coordinating feed plans with disease prevention and control

techniques. For instance, it has been demonstrated that dietary supplements like probiotics, prebiotics, and certain vitamins and minerals might improve fish immune responses and reduce their susceptibility to infections. Integrated pest management, or IPM, is becoming increasingly popular in aquaculture (Hubert *et al.,* 2021). This strategy uses a range of control techniques, including biological agents, disease-resistant breeding, environmental management, and, where required, targeted chemical treatments. In order to preserve ecological balance, IPM promotes a comprehensive approach that aims to reduce insect numbers below dangerous thresholds rather than eradicate them. In certain studies, combining disease-resistant strains with optimal dietary regimens has worked well. For example, Probiotics in feed and biocontrol agents have greatly decreased sea lice outbreaks in salmon aquaculture, increasing fish welfare and lowering financial losses. Other case studies in shrimp farming demonstrate the efficacy of polyculture systems in which shrimp are produced alongside species like tilapia. These systems help manage disease levels via natural microbial competition. By reducing chemical inputs and fostering biodiversity within aquaculture systems, these examples highlight the advantages of integrated techniques, promoting healthier aquatic species and improving environmental sustainability (Thomas *et al.,* 2021).

Challenges and Future Directions in Fish Feed and Disease Management

The current issues in fish feed and disease control are directly related to balancing sustainability, affordability, and nutrition. A significant challenge is creating affordable and nutrient-dense feeds as the industry looks for alternate sources of protein and fat due to the growing costs of conventional components like fishmeal and fish oil (Nunes *et al.,* 2022). Although they have potential, sustainable solutions like plant-based components, insect proteins, and microbial biomass have drawbacks that affect acceptance, such as digestibility, anti-nutritional effects, and customer hesitation. Because many nations have stringent regulations on acceptable feed ingredients to guarantee food safety, environmental sustainability, and traceability, regulatory standards make the development process even more difficult (Trienekens *et al.,* 2008). Despite their importance, these rules may raise production costs and restrict the variety of ingredients available. Growing consumer desire for fish-fed natural or organic ingredients increases pressure for transparency and ethical procedures as consumers become more conscious of sustainability and health issues in aquaculture goods. Promising approaches to reducing disease susceptibility without overusing antibiotics include probiotics, customized microbiome therapies, and functional meals enhanced with immune-boosting substances. The incorporation of precision aquaculture, where sensors and data analytics monitor feed efficiency, health, and environmental variables to enable real-time nutrition and health management modifications, is another trend for the future. Establishing balanced, sustainable, and creative solutions that improve fish health and production while tackling economic and ecological concerns will require cooperation between industry, academics, and politicians (Stead *et al.,* 2019).

Summary

Sustainable aquaculture methods are critical to meeting the world's expanding seafood demand while protecting natural ecosystems. The necessity of sustainable methods in feed formulation, disease prevention, and environmental management is emphasized in this paper. The advantages of plant-based and alternative protein sources in lowering reliance on fishmeal and fish oil, hence lessening stress on wild fish supplies, are among the main conclusions. Probiotics, immunostimulants, and biosecurity measures are examples of effective disease control tactics essential for lowering the need for antibiotics and preventing the spread of illness, both of which are critical for the health of the environment and food safety. Additionally, there are potential ways to lessen pollution and nutrient loading in water bodies using water quality management techniques, including integrated multi-trophic aquaculture (IMTA) and recirculating aquaculture systems (RAS). It is advised that aquaculture professionals use sustainable feed components, strictly adhere to disease prevention guidelines, and consider putting in place systems that maximize environmental health and resource efficiency in light of these findings. Investigating novel feed sources like algae and insect protein is crucial for future studies, as is creating cutting-edge, environmentally and public health-compliant disease management techniques. Sustained work in these fields will help aquaculture remain viable in the long run and benefit global ecological preservation and food security.

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