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# Health Management Techniques for Sustainable Marine Aquaculture

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**Abstract** While Marine aquaculture meets the global demand for aquatic products, it also faces severe challenges in terms of ecological environment and disease risks. Health management technology, as the core of sustainable Marine aquaculture, can enhance the survival rate and disease resistance of farmed organisms through comprehensive measures such as environmental regulation, disease early warning, prevention and control, as well as nutritional and immune intervention, reduce the negative impact of aquaculture activities on the environment, and thus achieve the dual goals of stable and efficient production and ecological friendliness. This study systematically analyzed the factors influencing the health of farmed animals, introduced water quality monitoring and ecological regulation technologies, rapid diagnosis and early warning methods for diseases, as well as microecological strategies and nutritional immunization management approaches, and constructed a healthy farming model by taking white shrimp as an example. The practical results show that these health management strategies can significantly reduce the risk of major disease outbreaks and effectively increase the yield and quality of aquatic products. It can be seen from this that scientific health management provides strong support and valuable practical reference for the sustainable development of Marine aquaculture.

**Keywords** Marine aquaculture; Environmental regulation; Disease early warning; Microecology; Nutritional immunity

## 1 Introduction

In recent years, the development of Marine aquaculture seems to have become a global trend. In fact, it is not hard to understand: on the one hand, wild fishery resources have been declining over the years, and the catch in many sea areas has been difficult to return to the previous level; On the other hand, the demand for seafood has only increased and not decreased. Thus, aquaculture has naturally been pushed to the position of addressing the supply and demand gap (Reverter et al., 2020). This is particularly evident in Asia, where the aquaculture output of countries like China has consistently ranked among the top in the world. Nowadays, more than half of the aquatic products consumed by humans are farmed, which basically indicates that aquaculture has become the main supply. However, behind the continuous increase in output, there is no lack of cost - situations such as overly intensive aquaculture and improper selection of methods often cause problems such as water eutrophication, coastal ecological degradation, and disease spread, exerting pressure on both the Marine environment and the industry itself (Liu et al., 2024).

When discussing sustainable development, people often think of technology or policy, but what is truly indispensable is actually health management. Only when the farmed fish and shrimp are healthy, with stable growth and reliable output, can economic benefits and food safety keep up. Conversely, if management fails to keep up, once a disease breaks out, the death toll is likely to increase in a short period of time, not only causing losses to farmers but also further polluting the environment due to improper disposal of corpses or frequent use of drugs (Schar et al., 2021). Compared with post-event compensation, scientific health management places more emphasis on early prevention and early control. This can not only reduce the dependence on drugs such as antibiotics, but also lower the ecological burden (Garlock et al., 2024). From the quality of aquatic products to consumer health and the long-term development of the industry, all these effects are irreplaceable.

This study focuses on health management in sustainable Marine aquaculture, aiming to explore how to maintain the health of farmed organisms through environmental regulation, disease early warning, microecological strategies, and nutritional and immune management, etc., to achieve sustainable development of the aquaculture industry. The thesis mainly analyzes the main factors influencing the health of farmed organisms. Introduce the regulation techniques of the aquaculture environment; Take the breeding of white shrimp from South America as a case study to analyze the health management model. Through the discussion of the above content, it is expected to provide useful references for the healthy, green and sustainable development of the Marine aquaculture industry.

## 2 Factors Affecting the Health of Marine Aquaculture Species

### 2.1 Dynamic changes in water quality, temperature, salinity, and dissolved oxygen

In Marine aquaculture, water quality is not constant. Affected by weather, seasons and even daily management, various parameters will fluctuate accordingly. The changes in temperature, salinity and dissolved oxygen are the most obvious and also the most likely to cause problems for fish and shrimp. If the temperature suddenly rises or drops, even if the increase is not significant, it may disrupt their metabolic rhythms and cause their immunity to decline. The matter of salinity is more complicated. Heavy rain on the sea surface can dilute seawater, and in hot seasons, evaporation can increase salinity. These sudden changes can make it difficult for fish and shrimp to recover for a while (Qu et al., 2022). When dissolved oxygen is low, the manifestations of hypoxia often come very quickly. Especially at night, algae and organic matter in the water still consume oxygen, so the dissolved oxygen is the lowest in the early morning (Reverter et al., 2020). If substances such as ammonia nitrogen and nitrite accumulate too much in water, they will also impose a chronic burden on animals. It is precisely because these changes are often intertwined that it is particularly necessary to monitor indicators such as water temperature, salinity and dissolved oxygen on a daily basis. Measures such as oxygenation, water replacement and temperature adjustment should also be kept up in a timely manner to avoid additional pressure on farmed animals caused by environmental fluctuations.

### 2.2 Germplasm quality, immune status, and population density

When it comes to the factors of organisms themselves, germplasm is often more crucial than people imagine. Seedlings from healthy parents that have been bred through superior variety selection are usually more hardy and less prone to diseases. If the seedlings themselves carry pathogens or have degeneration problems, their growth and stress resistance will naturally be much weaker (Milijasevic et al., 2024). This is also the reason why the industry has been constantly emphasizing seedling quarantine and genetic improvement in recent years. The immune level is another major influencing factor. Insufficient nutrition, high environmental stress and other conditions can all weaken the immune function, making animals more vulnerable to bacteria taking advantage of the situation. Group density may seem like a management-level matter, but its impact often directly reflects on health. High-density stocking not only keeps fish and shrimp in a state of competition and tension for a long time, but also once diseases occur, the transmission speed will be astonishingly fast (Wang et al., 2023). Therefore, in actual production, strictly controlling the quality of seedlings, maintaining a good immune status, and combining it with an appropriate density can often significantly reduce the risk of diseases.

### 2.3 Feeding practices, stocking density, and stress control

The details of feeding and management often determine whether animals can remain healthy. For instance, when feeding, if there is too much feed left over, it will sink in the water and spoil, and the water quality will deteriorate very quickly. Too little or unbalanced nutrition can cause fish and shrimp to be underfed, weak and have a weakened immune system (Okon et al., 2024). Therefore, the feeding amount and feed formula should be determined based on the needs of different stages. They should neither be wasted nor starve the animals. Although stocking density may sound like a cliche, even if the seedlings are of high quality and the feed is good, an excessively high density can still lead to competition and deterioration of water quality (Zhu et al., 2023). By adjusting the density and managing by pool and stage, the pressure on individuals can be reduced. Another issue that is often overlooked is the problem of stress. Many times, diseases are not directly caused by pathogens, but rather due to animals being startled, injured or experiencing sudden changes in the environment, their immunity is weakened, making them more prone to illness. Therefore, during operation, violent disturbances should be minimized as much as possible.

For example, the net pulling and sorting should be gentle, sudden changes in water temperature and pH should be avoided, and a concealed environment should be appropriately provided to make animals feel safe (Komal et al., 2025). Reducing stress often significantly improves the immune status, thereby lowering the chance of disease occurrence (Costa et al., 2025).

## 3 Environmental Regulation Technologies in Aquaculture

### 3.1 Application and optimization of intelligent water quality monitoring systems (IoT)

Modern Marine aquaculture is gradually introducing Internet of Things (IoT) technology to achieve intelligent monitoring and regulation of water quality environment. Sensors deployed in aquaculture ponds and cages can measure parameters such as water temperature, pH, dissolved oxygen, salinity, and ammonia nitrogen in real time, and transmit the data to the management platform or mobile phone via wireless network. Once the indicators exceed the set threshold, the system will automatically issue early warning prompts to take measures in time (such as starting the aerator, adding fresh water or reducing feeding), significantly improving the efficiency of water quality management (Ende et al., 2024) and avoiding the lag of manual detection. Meanwhile, the large amount of water quality data collected, after analysis, can also provide a basis for optimizing aquaculture strategies.

### 3.2 Seaweed-based purification, microecological construction, and ecological floating island technology

Purifying the aquaculture water environment by applying ecological principles is an important way to achieve stable water quality. Among them, large algae such as seaweed can be used as biological purifying agents: they absorb nutrients such as nitrogen and phosphorus in water through photosynthesis, convert eutrophic substances into what is needed for their own growth, thereby reducing the accumulation of harmful substances such as ammonia nitrogen in water bodies (Rosati et al., 2025). At the same time, the oxygen released by seaweed can also increase the dissolved oxygen level in water. Microecological construction refers to the addition of beneficial microorganisms (such as nitrifying bacteria, Bacillus, photosynthetic bacteria, etc.) to establish a stable microbial community in water bodies. These beneficial bacteria decompose organic waste, transform toxic substances, and competitively inhibit the growth of pathogenic bacteria (Figure 1), maintaining the "bacteria-algae balance" of water quality (Liao et al., 2025; Rosati et al., 2025). Regular use of microbial preparations can help the aquaculture system form a benign microecology. Ecological floating island technology is a system that sets up floating carriers on the water surface to grow aquatic plants (including salt-tolerant plants), forming a system similar to artificial wetlands. Floating island plants absorb excess nutrients in water through their root systems, provide shade for farmed animals and buffer water temperature. This technology is often used in aquaculture tail water treatment to naturally purify the discharged wastewater and reduce the environmental pressure on the surrounding sea area (Medina et al., 2022).

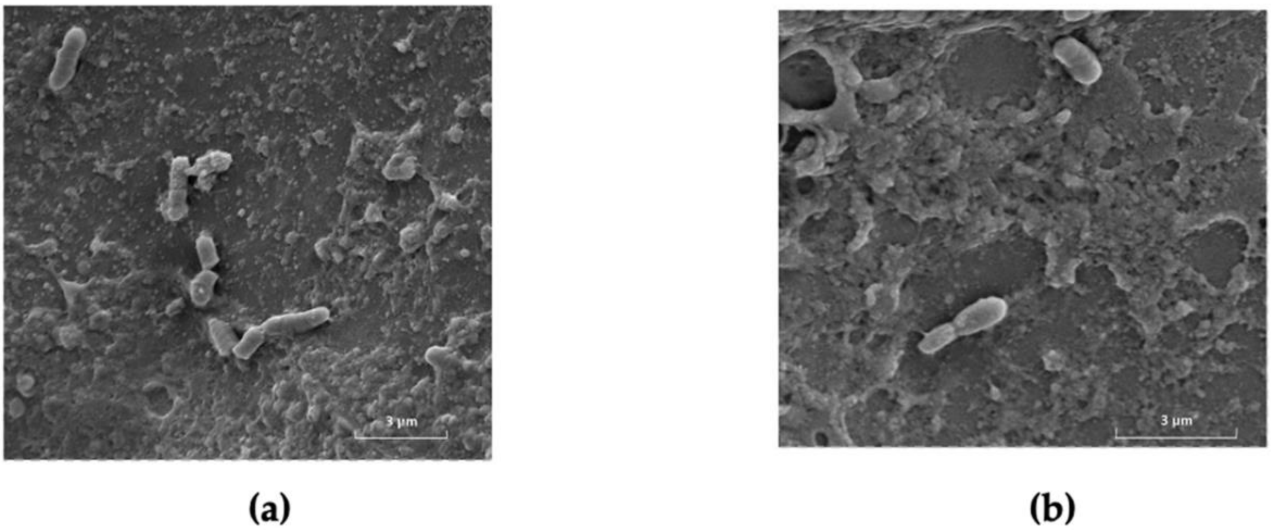


Figure 1 Scanning electron microscope (SEM) photo of microbial cells present on sea bass skin samples (Adopted from Rosati et al., 2025)

### 3.3 Aeration systems, recirculating aquaculture systems (RAS), and facility improvements

In actual production, many problems in aquaculture are often not due to any major issues with the fish and shrimp themselves, but rather because the facilities are not up to standard and the environment is difficult to stabilize. Oxygenation equipment is a typical example. Conventional devices such as waterwheel aerators and microporous aeration pipes are not installed to "improve technical levels", but because local hypoxia is very likely to occur in water bodies, especially when water layers differentiate (Jamil and Latip, 2023). Once the dissolved oxygen drops below the critical point, the machine must be turned on immediately; otherwise, the stress response of fish and shrimp will come very quickly, and in severe cases, they may even die. In fields with higher density, sometimes a pure oxygen system is also needed to support the oxygen consumption.

The idea of the circulating water system (RAS) is completely different. It is more like confining the water body in a controllable space. The system continuously purifies water through mechanical filtration, biological filters, ultraviolet disinfection and other processes, and then recycles it back into the pool for reuse. In this way, the frequency of water replacement can be reduced, and it is more difficult for external pathogens to enter. Many high-value varieties achieve stable year-round breeding precisely through this approach. As for the renovation of traditional facilities, they often seem insignificant, but the effect is very practical. For instance, laying anti-seepage membranes or installing bottom drains in ponds can help reduce the accumulation of harmful sediment. Indoor constant-temperature workshops and automatic feeding systems can reduce the interference caused by weather and human operation (Liao et al., 2025); After upgrading the structure of the offshore cages, both the water exchange rate and the ability to resist wind and waves will be better. Through these adjustments, the environment is more likely to remain within an acceptable range for animals, and thus they are less likely to develop diseases due to environmental stress.

## 4 Disease Early Warning and Diagnostic Techniques

### 4.1 Application of PCR, LAMP, and metagenomic sequencing in pathogen identification

In the early diagnosis of aquatic diseases, molecular detection has almost become a routine method, but the specific application varies depending on the scenario. For example, PCR is highly sensitive and targeted. The screening of many shrimp viruses is basically accomplished by it. For instance, detecting whether shrimp seedlings carry white spot syndrome virus (WSSV) is a common application (Ghosh et al., 2021). In some farms where equipment conditions are not so ideal, LAMP is actually more convenient. It does not require complex instruments. As long as the amplification is carried out at a constant temperature, the color change can be observed, and on-site personnel can also quickly judge the results. The situation of metagenomic sequencing is somewhat special. It does not focus on a specific pathogen but analyzes the DNA of all microorganisms in the sample together. This approach is particularly valuable when encountering diseases of unknown origin that cannot be detected by conventional tests (Wang et al., 2023). Although the cost is higher than the previous two types, it can provide key clues in sudden and unknown diseases. Combining the rapid detection of PCR and LAMP with the comprehensive analysis of metagenomics can basically establish a relatively complete framework for disease early warning and diagnosis, enabling prevention and control to be initiated earlier.

### 4.2 Intelligent diagnostic approaches based on imaging and behavioral monitoring

In recent years, many livestock farms have begun to rely on intelligent devices such as imaging and behavior monitoring to assist in assessing health conditions. Some people set up underwater cameras in fish ponds, while others install visual sensors in net cages. Combined with machine learning algorithms, they conduct round-the-clock observations of the fish population's conditions. When fish exhibit abnormal behaviors - such as swimming slowly, eating less, changes in body color, or even swimming alone (Grieb et al., 2020) - the system often captures these subtle changes earlier than humans. High-resolution images can also capture small lesions on the body surface. Through pattern recognition technology for preliminary judgment, it also avoids the easy omission of problems during manual pond patrols. In shrimp farming, another approach has also been attempted: using underwater acoustic sensors to listen to the feeding and activity sounds of shrimp flocks. Once the sound is abnormally quiet, it may indicate stress or disease (Du et al., 2025). These intelligent tools are equivalent to providing farms with a "non-tiring assistant", which can detect early signs and reduce the risk of large-scale outbreaks.

### 4.3 The role of health big data platforms in risk warning

Nowadays, aquaculture management is gradually moving towards digitalization. Many places have begun to build health big data platforms, concentrating data such as environmental monitoring, meteorological information, aquaculture records and historical diseases (Zeng et al., 2020). These data may seem disorganized to humans, but once handed over to machine learning models for processing, they can uncover the patterns of certain diseases that are prone to occur. For instance, when there is continuous high temperature combined with high density, the system may give a prompt indicating an increased risk of vibriosis and notify farmers in advance to pay attention to prevention and control. Or when the national monitoring network detects the spread trend of a certain new pathogen, the platform can also share the information immediately (Qian et al., 2024). In addition to early warnings, some platforms can also offer more specific suggestions, such as the timing of stocking seedlings, feeding strategies, or appropriately reducing the density during high-incidence seasons. With such big data support, managers no longer merely identify problems and then take remedial measures, but can make early plans and enhance the speed and stability of the entire industry in responding to epidemics.

## 5 Case Study: Development of a Sustainable Health Management Model for Pacific White Shrimp (*Litopenaeus vannamei*)

### 5.1 Challenges of early mortality syndrome (EMS) under high-density farming

The white shrimp of South America, as the shrimp species with the highest global farmed production, is prone to severe diseases under high-density farming models, among which the most representative one is Early Death Syndrome (EMS, also known as acute hepatopancreatic necrosis disease AHPND). This disease usually breaks out suddenly within 30 days after stocking, which can cause a large number of shrimp ponds to die, with a mortality rate as high as 100%. The pathogen of EMS is Vibrio parahaemolyticus carrying a specific virulence plasmid. When environmental conditions deteriorate or the immunity of shrimp is weakened, this bacterium multiplies in large quantities and produces toxins, causing acute death of shrimp (Fatima, 2025). High-density aquaculture environments provide a breeding ground for the prevalence of EMS: problems such as the accumulation of organic matter, fluctuations in dissolved oxygen, and elevated ammonia nitrogen in ponds are prominent. Shrimp individuals are in frequent contact, and the spread of bacteria is rapid (Wang, 2025). Furthermore, blindly increasing the stocking density in pursuit of yield will further weaken the immunity of shrimp (Ashour et al., 2024), significantly increasing the risk of EMS outbreak. The traditional response relying on antibiotics has little effect and is prone to induce drug resistance. There is an urgent need for an integrated health management model to prevent and control EMS.

### 5.2 Water quality regulation, microbial preparations, and immune enhancement strategies

When discussing EMS prevention and control, people often first think of the pathogen itself. However, in livestock farms, the actual matters to be dealt with are usually more trivial, and water quality, bacterial flora, and immunity all need to be taken into account simultaneously. In terms of water quality, it is not about pursuing overly complex technologies, but rather ensuring that the shrimp live in as stable and clean an environment as possible. Daily replacement of some pool water, treatment of tail water with sedimentation tanks or biological filters, along with continuous monitoring of dissolved oxygen, pH, ammonia nitrogen and other indicators, all fall under routine operations. Once the water quality begins to show some signs of deterioration, measures such as oxygenation and the addition of microbial agents should be taken as soon as possible to avoid leaving opportunities for the reproduction of pathogens. The concept of "treating water with bacteria" has been adopted by many farms. During the breeding process, probiotics such as bacillus, lactic acid bacteria, and photosynthetic bacteria are continuously introduced (Bussabong et al., 2021). They can not only seize the living space of pathogenic bacteria, but also decompose leftover feed and shrimp manure, preventing the deterioration of the bottom environment of the pond. As for the immunity of prawns themselves, some methods are also commonly used. For example, adding yeast glucan, extracts of Chinese herbal medicines, and antioxidants such as vitamin C and vitamin E to the feed (Figure 2) can enhance the non-specific immune response and enable prawns to resist pathogens more effectively (Rairat et al., 2024; Fatima, 2025). Long-term feeding of high-quality feed with functional additives is also beneficial to the health of the hepatopancreas. Some farmers also attempt to expose shrimp to attenuated pathogens by soaking or oral administration, thereby acquiring a certain degree of resistance. Although there is no mature vaccine for EMS at present, similar attempts do offer some possible directions for the future to some extent.

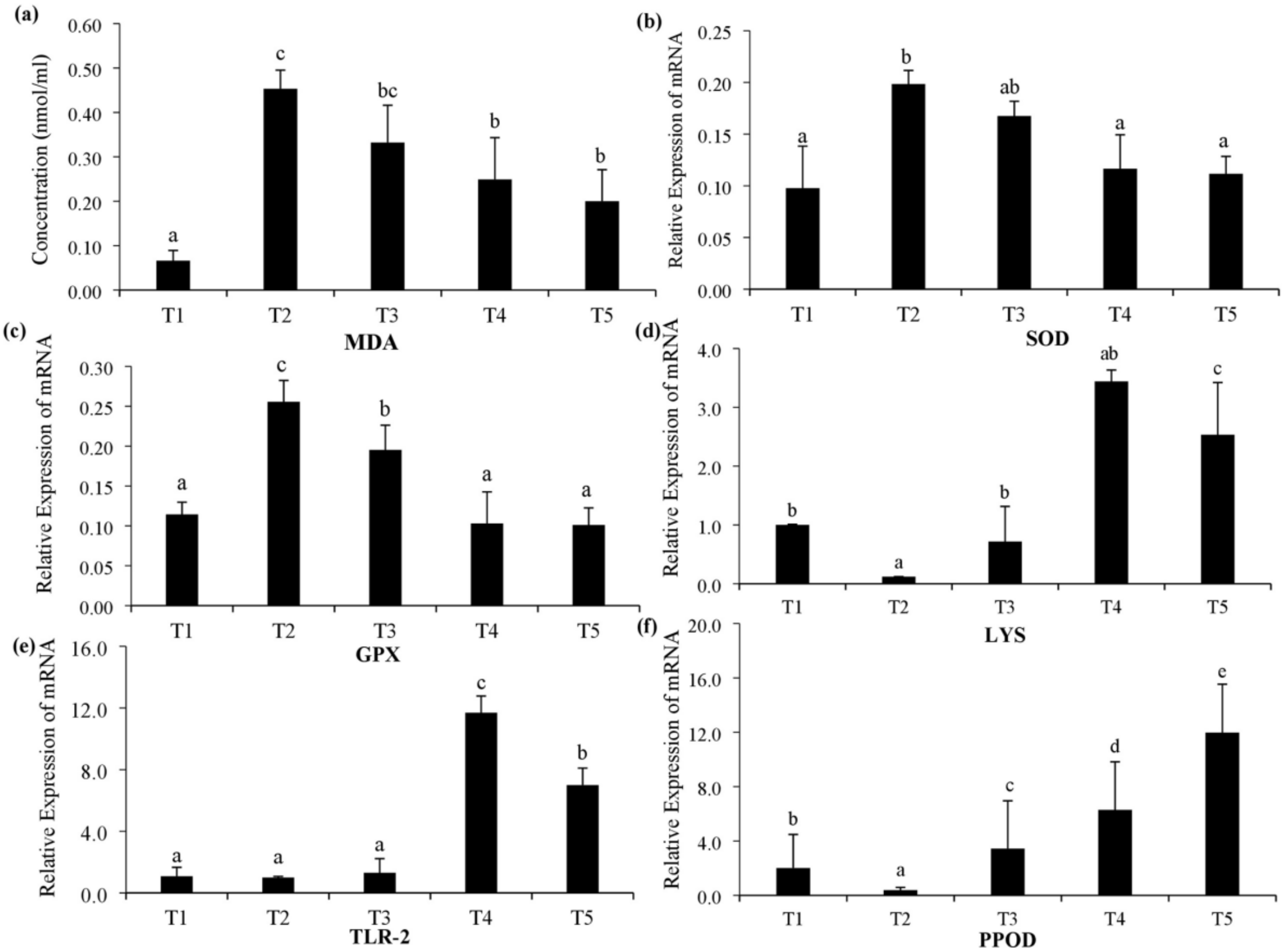


Figure 2 Concentration of malondialdehyde (MDA) in hemolymph measured by ELISA (a). Relative expression of mRNA of superoxide dismutase (SOD) (b), lysozyme (LYS) (c), glutathione peroxidase (GPX) (d), toll like receptor-2 (TLR-2) (e) and prophenolperoxidase (PPOD) (f) in four different treatments (T1, lows stocking density, T2, high stocking density, T3: lauric acid, T4: N-acetylcysteine, T5: lauric acid+N-acetylcysteine (Adopted from Fatima, 2025)

### 5.3 Improvements in survival rate, reduction of environmental load, and economic benefits

After adopting this comprehensive health management model, the farming performance of white shrimp from South America has generally undergone significant changes. The most obvious improvement is the increase in survival rate, which has risen from the originally common less than 50% to over 85%, and the situation of "pond drainage" has also become rare (Chuchird et al., 2021). Because there is no longer a reliance on frequent water changes or blind medication, the quality of the tail water has improved, the discharge has decreased, and the risk of eutrophication in the nearby waters has also declined accordingly. More importantly, after the reduction of diseases, production becomes more stable and income naturally increases. Although health management itself does require investment, when taken into account, the benefits in both ecological and economic aspects are more considerable.

## 6 Microecological Regulation Strategies in Healthy Aquaculture

### 6.1 Mechanisms of probiotics and microbial preparations in disease prevention

In the practice of animal husbandry, many people think of medication when it comes to disease prevention. However, in fact, probiotic microbial preparations have long been a commonly used method, and their effects are no less effective. Their functions are not singular; they often occur simultaneously in water bodies and the intestines. Common probiotics like Bacillus, once they gain dominance in water, will consume a large amount of organic matter, weaken the nutrient sources of pathogens such as Vibrio, and secrete some antibacterial substances (Milijasevic et al., 2024). In addition, some bacteria can produce by-products such as organic acids, enzymes and vitamins, which make the water quality and intestinal environment more conducive to the digestion and absorption of animals, and improve their appetite and nutritional status as a result. More interestingly, after these probiotics colonize in animals, they can also stimulate the immune system, increase indicators such as phagocyte activity and lysozyme levels, thereby enhancing disease resistance (Wani et al., 2025). It is precisely because of the combined effects of several aspects that probiotics have gradually become an important alternative to antibiotics, which is also relatively consistent with the direction of green breeding.

### 6.2 Construction of biofloc technology (BFT) and its health effects

BFT may seem like a new technology, but the core idea is actually quite simple: allowing microbial communities to "work on their own" in water. By adding carbon sources to adjust the carbon-nitrogen ratio to a range suitable for the rapid reproduction of heterotrophic bacteria, the harmful ammonia nitrogen will be converted by these bacteria into their own proteins, eventually forming flocculent masses that can be consumed by animals such as prawns (Wandana et al., 2024). These flocs are not only a source of nutrients but also a key factor in maintaining water quality stability. Due to the large number of heterotrophic bacteria, toxic nitrogen in the system is not easy to accumulate, and pathogenic bacteria (especially vibrio) also find it difficult to gain an advantage in such a microecosystem. In order to keep the flocs suspended and active all the time, the BFT system usually requires strong aeration and smooth water circulation; otherwise, microbial activity will decline (Rahman et al., 2023). An environment with high dissolved oxygen and rich bacterial flora is often very beneficial for farmed animals. Not only do they grow well, but the incidence rate is also lower. It can be said that BFT accomplishes both "purifying water quality" and "providing nutrients" simultaneously through microbial ecological engineering.

### 6.3 Maintaining microecological diversity and water stability

In healthy aquaculture, microbial diversity is often overlooked, but its role is as important as that of water quality indicators. A diverse microbial community can undertake more functions, such as organic matter degradation, nitrogen cycling, and pathogen inhibition. Once these functions are shared by different microbial communities, the system will be more "resilient" when encountering environmental changes. Like in a pond with a relatively balanced algal and bacterial structure, even if a certain type of algae suddenly decreases, other algae can replace it in time and will not cause sharp fluctuations in water quality (Canak et al., 2023). To maintain this diversity, the abuse of broad-spectrum antibacterial agents should be avoided as much as possible in daily management. Otherwise, both beneficial and harmful bacteria will be eliminated together, making the system more prone to imbalance. At the same time, different types of probiotics can be alternately administered or compound bacterial agents can be used to make the ecological structure more stable (Guo et al., 2023). In addition, the feeding of feed and the control of water quality should not be extreme either; otherwise, certain types of microorganisms may grow out of control due to overly biased conditions. Only when the micro-ecological structure remains rich and balanced can water bodies remain stable for a long time and be less likely to experience sudden deterioration or disease outbreaks.

## 7 Nutrition and Immune Management of Aquaculture Species

### 7.1 Optimization of amino acids, fatty acids, and vitamin supply

In aquaculture production, feed is often regarded as a "cost", but what truly determines the physical condition of fish and shrimp is whether the nutritional ratio is in place. The amino acid part is often overlooked, especially when plant protein is used to replace fish meal. The problem of low content of essential amino acids such as lysine and methionine will be exposed. If no additional supplementation is provided, the growth of animals is likely to stagnate and their immunity will also decline. The situation of fatty acids is somewhat different. Marine fish and shrimp themselves have a high demand for omega-3 long-chain polyunsaturated fatty acids such as DHA and EPA. HUFA is not only an important component of cells, but also related to anti-inflammatory, anti-stress and other abilities (Milijasevic et al., 2024). Adding an appropriate amount of high-quality fish oil or algal oil to feed can often significantly improve the fatty acid composition in the body and enhance disease resistance. As for vitamins, although the demand seems not large, the problems that arise when lacking them are quite obvious. For example, when there is insufficient vitamin C and E, the antioxidant capacity is weak, wound healing is slow, and it is also more likely to have problems when encountering stress (Visudtiphole et al., 2025). Therefore, regularly testing the nutritional components of feed and promptly adjusting the supply of amino acids, fatty acids and vitamins is a simple yet effective way to avoid nutritional health problems.

### 7.2 Application of prebiotics, immunostimulants, and plant extracts

Adding functional additives to feed is an important means to improve the health level of farmed animals. Prebiotics, as the "nourishment" for probiotics, can promote the reproduction of beneficial bacteria in the intestines, improve the balance of the microbial community, and thereby enhance the digestive and absorptive capacity and disease resistance of farmed animals. For example, adding oligosaccharide substances to shrimp and fish feed can often increase the number of intestinal lactic acid bacteria and reduce the level of harmful bacteria (Abhiram et al., 2025). Immunostimulants directly activate the immune system of animals and enhance their non-specific immune responses. Commonly used substances of this kind include yeast polysaccharides, β -glucan, etc., which can enhance the activity of immune factors such as phagocytes and lysozyme, putting fish and shrimp in a better state of disease resistance. Plant extracts, as natural health-promoting additives, are also attracting increasing attention. Many Chinese herbal medicines (such as garlic, astragalus, etc.) contain antibacterial, antioxidant and immunomodulatory components. Appropriate addition can play the role of inhibiting bacteria, preventing diseases and enhancing physical fitness (Leyva-Lopez et al., 2020). The rational combined use of these additives can reduce the dosage of antibiotics, prevent the occurrence of diseases without harming the health of animals, and promote the development of the animal husbandry towards a greener and safer direction.

### 7.3 Oral vaccines, nanoparticle-based agents, and immune monitoring

In actual operation, it is very difficult to administer vaccines to each fish or shrimp one by one, which is also the reason why oral vaccines are receiving increasing attention. Feeding animals with antigen packages in feed can induce a certain immune response and at least reduce the stress caused by the operation. However, oral vaccines also have weaknesses. Antigens are easily decomposed in the intestine. Therefore, researchers have begun to use carriers such as microcapsules and nanoparticles to protect antigens and improve absorption efficiency, thereby enhancing the immune effect (Jin et al., 2021). Similar nanotechnology is also used in antibacterial agents or immunomodulators, such as making plant extracts into nanoparticles to enhance their activity and duration of action. However, when using it, attention should also be paid to the dosage and potential environmental impact. At the same time, immune monitoring should not be ignored. Regularly measuring antibody titers, lysozyme activity and other indicators can help breeders determine earlier whether the animal's immunity has declined. If a downward trend in the immune status is detected, nutritional supply can be adjusted in advance, water quality improved or other interventions taken to prevent minor issues from escalating into large-scale diseases.

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## Conflict of Interest Disclosure

The authors confirm that the study was conducted without any commercial or financial relationships and could be interpreted as a potential conflict of interest.

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