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Review and Progress **Open Access**

Research Progress on Key Technologies for Disease Prevention and Control in Shrimp Aquaculture

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Abstract This study reviews the research progress and development trends of key technologies for disease prevention and control in shrimp aquaculture. With the shift toward high-density and intensive farming systems, viral, bacterial, and parasitic diseases have become increasingly prevalent, posing significant constraints on the sustainable development of the industry. This paper systematically summarizes the major disease types and their epidemiological characteristics, and analyzes the effects of pathogen-host interactions, environmental factors, and farming practices on disease occurrence. On this basis, recent advances in disease detection and monitoring technologies are reviewed, including conventional methods, molecular and immunological techniques, as well as rapid detection and intelligent monitoring systems. Furthermore, key prevention and control strategies are discussed, such as aquaculture management and ecological regulation, microbial modulation and antibiotic alternatives, immunostimulation, and disease-resistant selective breeding, along with their application outcomes. The current challenges are also addressed, including pathogen variation and emerging disease risks, antibiotic misuse and antimicrobial resistance, and the lack of technology transfer and standardization. Finally, future perspectives are proposed, highlighting a transition toward integrated management approaches centered on biosecurity. This study provides a reference for developing green, efficient, and sustainable shrimp health management systems.

Keywords Shrimp aquaculture; Disease control; Biosecurity; Microbial regulation; Intelligent monitoring

1 Introduction

With the rapid development of global aquaculture, shrimp farming has become one of the fastest-growing and most economically valuable sectors. It not only provides an important source of animal protein for regions such as Asia and Latin America, but also generates substantial export revenues. Among the major cultured species, Pacific white shrimp (*Litopenaeus vannamei*) and Chinese shrimp have been widely promoted worldwide due to their rapid growth, strong environmental adaptability, and high market demand. In crustacean aquaculture, marine shrimp dominate both production volume and economic value. However, while high-density and intensive farming systems have significantly increased production, they have also intensified environmental pressure and reduced system stability, leading to increasingly severe disease problems that have become a major bottleneck for sustainable industry development (Bhassu et al., 2024).

In recent years, viral and bacterial diseases have repeatedly occurred in major shrimp farming regions worldwide. Typical diseases include white spot syndrome virus (WSSV), acute hepatopancreatic necrosis disease (AHPND), Enterocytozoon hepatopenaei (EHP) infection, and vibriosis. These diseases are characterized by rapid transmission and high mortality, often causing large-scale outbreaks and severe economic losses within a short period (Chowdhury et al., 2024). Since the 1990s, such diseases have frequently affected major aquaculture countries such as India and Thailand, resulting in cumulative losses of billions of dollars. Studies have shown that disease outbreaks are not only closely associated with pathogenic microorganisms, but are also driven by multiple factors, including water quality deterioration, environmental degradation, inadequate biosecurity measures, and the globalization of seedstock and live animal trade. Their impacts extend beyond production losses to include reduced employment and socio-economic instability in coastal regions (Bhassu et al., 2024; Chowdhury et al., 2024).

Therefore, effective disease prevention and control has become a critical component for ensuring shrimp health and maintaining industry stability. Traditional approaches based on antibiotics, chemicals, and disinfectants may provide short-term benefits, but are limited in controlling viral pathogens. Long-term use can also induce antimicrobial resistance in Vibrio spp., disrupt host microbial communities, and pose risks to the environment and food safety (Khanjani et al., 2024). In addition, due to the lack of a typical adaptive immune system in shrimp, the application of conventional vaccination strategies remains limited. As a result, preventive health management approaches have gradually become the mainstream, including strengthening biosecurity systems, using specific pathogen-free (SPF) and disease-resistant (SPR) stocks, optimizing culture environments, and applying functional feed additives for immune regulation (Nguyen, 2024). However, disease outbreaks remain frequent in practice; for example, nearly half of the production cycles in some regions are affected by diseases, indicating that single management strategies are insufficient to control complex disease systems (Bhassu et al., 2024).

This study aims to review the progress of green, efficient, and sustainable technologies for disease prevention and control in shrimp aquaculture. Advances in pathogen detection technologies, such as PCR, quantitative real-time PCR, monoclonal antibody-based assays, and lateral flow test strips, have significantly improved detection sensitivity and accuracy. Meanwhile, emerging technologies, including high-throughput sequencing, nanotechnology, biosensors, RNA interference, and CRISPR-Cas systems, have enhanced our understanding of pathogen–host interactions and provided valuable tools for disease-resistant genetic improvement. In addition, microbial-based products such as probiotics, prebiotics, and synbiotics, as well as bioactive compounds derived from plants and microalgae, have shown promising potential in regulating gut microbiota, enhancing immunity, and improving disease resistance. This study systematically analyzes major disease types and their epidemiological characteristics, examines key mechanisms and influencing factors, and reviews advances in biosecurity systems, SPF/SPR breeding, immunostimulants and functional additives, microbial regulation, and molecular and omics technologies. Finally, future development trends are discussed to provide a theoretical basis and practical reference for establishing green, efficient, and sustainable shrimp health management systems.

2 Major Disease Types and Epidemiological Characteristics in Shrimp Aquaculture

2.1 Major disease types

Shrimp aquaculture is affected by a wide range of diseases, among which viral, bacterial, and parasitic infections are the most common. These diseases have significant impacts on survival rate, growth performance, and overall economic returns. Previous studies have shown that viral diseases account for the majority of losses in shrimp farming, contributing approximately 60% of total disease-related losses, while bacterial diseases account for about 20%. Fungal and parasitic diseases generally occur at lower frequencies but can still cause substantial damage under specific environmental conditions (Hasan et al., 2024). Therefore, a systematic understanding of major disease types from a pathogen spectrum perspective is essential for establishing healthy aquaculture systems and implementing precise disease control strategies.

Viral diseases are widely regarded as the most severe threat in shrimp aquaculture. They are characterized by rapid transmission, high mortality, and a broad host range, and can easily cause outbreaks under high-density farming conditions. Major viral diseases of concern include white spot syndrome caused by white spot syndrome virus (WSSV), Taura syndrome caused by Taura syndrome virus (TSV), yellow head disease caused by yellow head virus (YHV), as well as infections caused by infectious hypodermal and hematopoietic necrosis virus (IHHNV) and infectious myonecrosis virus (IMNV). These pathogens can enter aquaculture systems through infected seedstock, broodstock carriers, waterborne transmission, and farming practices, and can rapidly spread under conditions of environmental deterioration or host stress. Due to their high pathogenicity and potential for transboundary spread, many shrimp viruses have been listed as notifiable pathogens by the World Organisation for Animal Health.

Bacterial diseases are mainly associated with infections by Vibrio spp., which are among the most common disease types under conditions of high temperature, high organic load, and poor management. Vibrio infections can cause clinical manifestations such as red body disease, septicemia, and hepatopancreatic damage. Among them, acute hepatopancreatic necrosis disease (AHPND), caused by specific strains of Vibrio parahaemolyticus carrying virulence plasmids, is of particular concern. In addition, V. harveyi, V. alginolyticus, V. cholerae, and V. vulnificus can also act as primary or opportunistic pathogens (Chowdhury et al., 2024). Compared with viral diseases, bacterial infections are theoretically more controllable; however, due to their strong virulence, environmental adaptability, and increasing antimicrobial resistance, disease management is becoming more challenging.

2.2 Characteristics and impacts of typical diseases

Among various shrimp diseases, white spot syndrome virus (WSSV) and acute hepatopancreatic necrosis disease (AHPND) are considered the most widespread and economically devastating. WSSV is one of the most representative and highly pathogenic viruses in shrimp aquaculture. It is an enveloped double-stranded DNA virus with a broad host range, capable of infecting multiple decapod crustaceans and establishing persistent low-level infections in hosts. Under favorable conditions, infections can rapidly escalate into outbreaks. Clinical signs of WSSV infection include white calcified spots on the exoskeleton, reddish discoloration, reduced feeding, lethargy, and rapid mortality (Hasan et al., 2024). Studies have shown that WSSV outbreaks can result in cumulative mortality rates of 80%-100% within 3-10 days, demonstrating acute onset, high lethality, and strong transmissibility (Hasan et al., 2024).

Compared with WSSV, AHPND is a rapidly emerging bacterial disease that predominantly affects early culture stages. It is caused by specific strains of Vibrio parahaemolyticus carrying virulence plasmids encoding PirAB toxins. These toxins directly damage the hepatopancreas, leading to massive epithelial cell sloughing, necrosis, and functional failure. AHPND typically occurs within 20-30 days after stocking and is characterized by reduced feeding, empty gut, hepatopancreatic atrophy, and discoloration. Due to the lack of obvious external symptoms in some cases, early diagnosis is challenging. In severe outbreaks, mortality rates can exceed 70%, particularly affecting juvenile shrimp. The disease has been reported in multiple countries, including China, Vietnam, Thailand, and Mexico, and its spread is closely associated with seedstock movement, inadequate biosecurity, and environmental stress.

In addition to WSSV and AHPND, diseases such as Taura syndrome (TSV), yellow head disease (YHV), infectious myonecrosis (IMNV), and EHP infection also pose significant threats. Unlike acute high-mortality diseases, EHP infection typically causes chronic impacts, including slow growth, size variation, reduced feed efficiency, and prolonged culture periods, thereby reducing overall productivity. From an industrial perspective, shrimp diseases can be categorized into “acute lethal diseases” and “chronic debilitating diseases,” both of which contribute to economic losses. Moreover, pathogens do not act independently. Studies have shown that co-infection with AHPND and WSSV can exacerbate tissue damage and increase mortality. WSSV exposure can also enhance the susceptibility of Litopenaeus vannamei to AHPND-causing Vibrio strains. Therefore, disease understanding should extend beyond single pathogens to a framework incorporating multi-pathogen interactions and host stress responses.

2.3 Epidemiological Patterns of Diseases

Shrimp diseases exhibit pronounced seasonal patterns, closely associated with water temperature, salinity, water quality fluctuations, and farming-related stress. Studies have shown that WSSV outbreaks are strongly influenced by temperature variations. The virus shows high virulence at temperatures of approximately 25 °C-28 °C, while sudden temperature drops or low-temperature conditions can increase host stress and mortality rates (Hasan et al., 2024). In contrast, Vibrio pathogens proliferate rapidly under high temperature, high organic load, and low dissolved oxygen conditions, making bacterial diseases more prevalent during hot seasons. In addition, factors such as heavy rainfall, improper water exchange, and sediment deterioration can cause ammonia accumulation, pH fluctuations, and microbial imbalance, thereby increasing disease outbreak risks (Chowdhury et al., 2024).

These findings indicate that seasonal effects operate through combined influences on host physiology and environmental conditions.

Shrimp diseases also show clear regional variability. The dominant pathogen spectrum and epidemiological patterns differ among regions. Asia has experienced multiple disease outbreaks, including WSSV, YHV, AHPND, and EHP, making it one of the most complex and high-risk regions globally. In contrast, the Americas were initially dominated by TSV and WSSV, with increasing reports of AHPND in recent years. Even within a single country, significant differences may exist among farming areas. For example, studies in the east coast of India have shown varying combinations of EHP, Vibrio spp., and WSSV across different farming systems and regions. Coastal high-density farming areas generally face higher outbreak risks due to frequent seedstock movement and pathogen introduction, whereas inland low-salinity systems may experience lower disease frequency but still suffer significant losses once outbreaks occur due to limited monitoring capacity.

Furthermore, co-infection has become a prominent feature of shrimp disease epidemiology. Field observations and experimental studies indicate that multiple pathogens can coexist within the same system or host, such as EHP–WSSV and Vibrio–WSSV co-infections (Chowdhury et al., 2024). These co-infections often exhibit synergistic pathogenic effects rather than simple additive impacts. Viral infections can weaken host immune defenses and damage tissue barriers, facilitating bacterial invasion. Conversely, bacterial infections can promote viral replication through tissue damage and inflammatory responses. As a result, multi-pathogen interactions often lead to higher mortality rates, more complex clinical manifestations, and increased difficulty in diagnosis and disease control.

3 Mechanisms and Influencing Factors of Shrimp Diseases

3.1 Pathogen-host interactions and immune mechanisms

The occurrence of shrimp diseases is essentially the result of an imbalance among pathogens, the host innate immune system, and environmental factors. As invertebrates, shrimp lack a typical adaptive immune system and long-term specific immune memory; thus, their defense against infections mainly relies on innate immunity. This system consists of both cellular and humoral components, including phagocytosis, encapsulation, coagulation, and activation of the prophenoloxidase system. In addition, effector molecules such as antimicrobial peptides, lectins, and lysozymes play critical roles in immune defense. Upon pathogen invasion, the host initially recognizes pathogen-associated molecular patterns (PAMPs) via pattern recognition receptors (PRRs). This recognition subsequently activates key signaling pathways, such as NF-κB and JAK/STAT, leading to the expression of various immune effectors that contribute to pathogen clearance and restriction of their spread in hemolymph and tissues.

However, the intensity and duration of innate immune responses in shrimp are relatively limited, making it difficult to establish long-term protection similar to that observed in vertebrates. Consequently, shrimp are more susceptible to infections and disease outbreaks under conditions of high pathogen pressure or environmental stress. Transcriptomic and immunological studies have shown that multiple immune pathways are significantly modulated following infection with white spot syndrome virus (WSSV) or AHPND-causing Vibrio. Meanwhile, many pathogens have evolved sophisticated immune evasion and host manipulation strategies. For example, WSSV can interfere with host signal transduction, apoptosis, and antiviral responses, thereby creating a cellular environment favorable for viral replication and dissemination (Xiong et al., 2024). Therefore, pathogen-host interactions represent a dynamic and continuous interplay rather than a simple unidirectional process of host defense versus pathogen invasion.

In bacterial diseases, the pathogenic mechanisms of AHPND also demonstrate strong pathogen adaptability. The causative Vibrio parahaemolyticus strains typically harbor the pVA1 virulence plasmid encoding PirAB toxins, which directly damage hepatopancreatic tissues, leading to epithelial cell sloughing and necrosis. This enables rapid disruption of local immune defenses and results in high mortality (Chandran et al., 2023). Furthermore, an imbalance in host immune responses can exacerbate disease progression. Excessive inflammatory responses may cause additional tissue damage, whereas insufficient immune responses fail to effectively control pathogen proliferation. Therefore, disease outcomes depend not only on pathogen load but also on the regulation of host immune responses (Chandran et al., 2023).

3.2 Environmental factors

Environmental factors play a crucial role in shrimp health and disease occurrence. Their effects are reflected not only in regulating pathogen survival and transmission, but also in influencing host physiological homeostasis and immune competence. Among various environmental variables, water quality is one of the most critical. Parameters such as dissolved oxygen, pH, partial pressure of carbon dioxide, ammonia, and nitrite directly affect shrimp metabolism, osmoregulation, and immune function. When shrimp are exposed to suboptimal water conditions, either in the short or long term, they exhibit physiological stress responses accompanied by reduced hemocyte function, suppressed phenoloxidase activity, and weakened resistance to infection, thereby increasing mortality risk upon pathogen exposure (Hapsari et al., 2025). In addition, the accumulation of uneaten feed and waste elevates organic load, providing favorable conditions for opportunistic pathogens such as Vibrio spp.

Temperature is another key factor influencing disease dynamics. Studies have shown that WSSV exhibits high virulence at approximately 25 °C-28 °C, whereas higher temperatures (e.g., >30 °C) may reduce outbreak severity under certain conditions. However, the impact of temperature depends not only on absolute values but also on the magnitude and rate of fluctuations. Extreme weather events, such as cold spells, heatwaves, and large diurnal temperature variations, can induce significant physiological stress, impair immune function, and trigger the transition from latent to active infections (Chang et al., 2024). Therefore, maintaining stable temperature conditions is often more critical than controlling absolute temperature levels in aquaculture practice.

Salinity is also an important environmental determinant of shrimp health. Deviations from optimal salinity levels increase osmoregulatory stress and disrupt physiological balance, thereby reducing disease resistance. Rapid declines in salinity, often caused by heavy rainfall, large-scale water exchange, or low-salinity farming systems, are closely associated with outbreaks of AHPND and vibriosis (Chang et al., 2024). Recent studies further indicate that low-salinity stress not only affects host osmoregulation but also reduces gut microbiota diversity and alters microbial community functions. These changes can promote the proliferation and tissue invasion of pathogenic Vibrio strains, suggesting that salinity influences disease dynamics through multi-level interactions among host, microbiota, and pathogens (Chang et al., 2024).

3.3 Effects of farming systems and stress factors

Farming systems largely determine the levels of biotic and abiotic stress experienced by shrimp and thus represent key management factors influencing disease occurrence. High-density intensive aquaculture systems have significantly increased production efficiency but also elevated pathogen transmission rates, water quality deterioration risks, and chronic stress levels, thereby increasing disease incidence (Hapsari et al., 2025; Kumar et al., 2025). Under high stocking densities, increased contact among individuals facilitates rapid pathogen spread. Meanwhile, the accumulation of uneaten feed and metabolic waste increases environmental load, further promoting the growth of opportunistic pathogens such as Vibrio spp.

Site selection and farming infrastructure also influence disease risks. Aquaculture systems established in acid sulfate soils, polluted waters, or ecologically marginal environments may expose shrimp to acidification, heavy metals, or other contaminants, thereby increasing physiological stress and weakening disease resistance (Kumar et al., 2025). In addition, the large-scale transboundary movement of broodstock and seedstock, particularly in the absence of strict quarantine and biosecurity measures, has been identified as a major pathway for pathogen dissemination and a key driver of historical disease outbreaks.

Operational stressors in daily management further contribute to disease occurrence. Activities such as harvesting, grading, transportation, stocking, water exchange, and pond transfer can disrupt physiological and endocrine balance and suppress innate immune functions (Hapsari et al., 2025). In particular, improper management during early stocking stages or periods of abrupt environmental change can trigger the transition from subclinical infections to overt disease outbreaks. Chronic or repeated stress can also lead to long-term health impairment, manifested as reduced feeding, slower growth, and decreased survival rates. Moreover, the gut microbiota plays an important mediating role in this process. High-density culture and nutritional imbalance can disrupt microbial homeostasis, resulting in reduced beneficial bacteria and increased opportunistic pathogens, thereby further elevating disease risk (Chang et al., 2024; Murugan et al., 2024; Xiong et al., 2024).

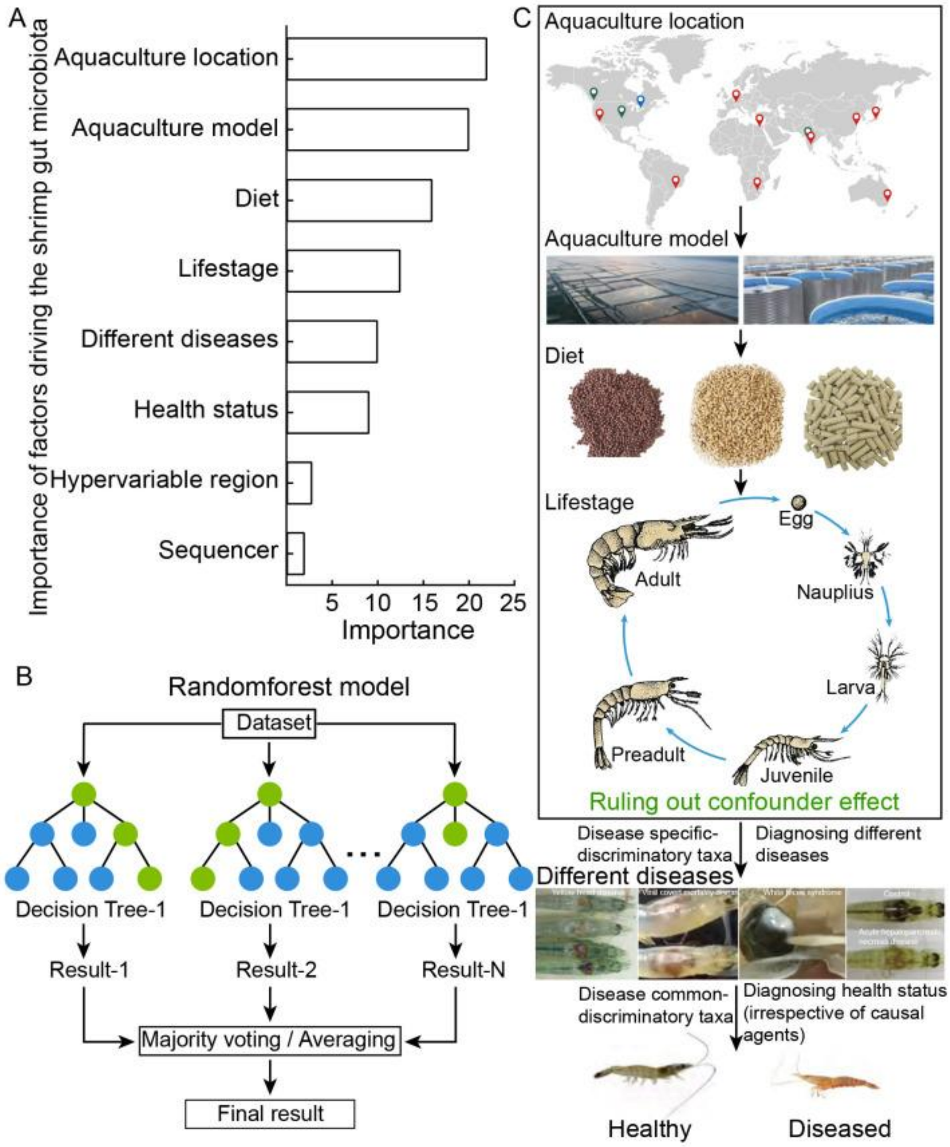

Figure 1 Flowchart screening disease common-discriminatory taxa for diagnosing shrimp health status (Adopted from Xiong et al., 2024)

Image caption: A: Quantifying relative importance of factors governing shrimp gut microbiota in descending order. B: Identifying discriminatory taxa for each factor using a random forest model. C: Identifying disease common-discriminatory taxa after progressive removal of effects of factors more important than health status in governing gut microbiota (Adopted from Xiong et al., 2024)

4 Advances in Disease Detection and Monitoring Technologies

4.1 Conventional detection methods and their limitations

In the early stages of shrimp disease diagnostics, conventional approaches primarily relied on clinical observations and classical laboratory techniques. These methods include visual inspection, microscopic examination, histopathological analysis, electron microscopy, and culture-based isolation of cultivable bacteria. In practical aquaculture, diseases are often preliminarily diagnosed based on external symptoms such as abnormal body coloration, appendage damage, white spots on the carapace, and empty gut. Post-mortem observations, including hepatopancreatic atrophy, gill damage, and muscle necrosis, are also used as supporting indicators. Parasitic infections and some bacterial pathogens can be identified morphologically using optical microscopy, while bacterial pathogens are typically isolated and characterized through culture and biochemical tests. These methods are technically mature and cost-effective, and they remain useful in small-scale farming operations and routine laboratory diagnostics.

However, conventional methods have clear limitations in terms of sensitivity, specificity, timeliness, and field applicability. Many important viral diseases lack specific clinical symptoms in the early stages, and some individuals may carry subclinical infections, making early detection based solely on visual observation unreliable (Zwetlana et al., 2023). In addition, morphological similarities among parasites, bacteria, and pathological changes can lead to misdiagnosis. For key viral pathogens such as WSSV, TSV, and DIV1, the lack of stable and applicable cell culture systems limits the effectiveness of traditional isolation and culture-based methods (Lee et al., 2023). Furthermore, culture-based techniques have limited ability to detect Vibrio spp. in the viable but non-culturable (VBNC) state, often underestimating the actual pathogen load (Bohara et al., 2023).

Conventional methods are also constrained by long detection cycles. Histopathology, microbial culture, and serological assays typically require several days to weeks and depend on specialized laboratories and trained personnel, which is inadequate in rapidly evolving disease scenarios (Bohara et al., 2023). In screening broodstock, seedstock, and asymptomatic carriers, these methods often fail to detect low-level infections, even though such carriers play a critical role in disease transmission (Zwetlana et al., 2023). Therefore, with the expansion of intensive aquaculture and global trade, traditional diagnostic approaches are no longer sufficient for precise diagnosis and early warning, driving the development of highly sensitive molecular and rapid detection technologies.

4.2 Molecular and immunological detection technologies

The widespread application of molecular biology has significantly advanced shrimp disease diagnostics from empirical observation to standardized and highly sensitive detection. Among these, nucleic acid amplification techniques have become the cornerstone of pathogen detection. Conventional PCR, nested PCR, quantitative real-time PCR (qPCR), loop-mediated isothermal amplification (LAMP), and recombinase polymerase amplification (RPA) have been widely applied for detecting major pathogens, including WSSV, IHHNV, DIV1, TSV, YHV, IMNV, as well as AHPND-causing Vibrio and EHP (Lee et al., 2023; Lou et al., 2025). These methods enable the detection of low-abundance nucleic acids, allowing early identification of pathogens during latent or initial infection stages, thereby supporting timely management decisions.

Among nucleic acid-based methods, qPCR has become the most widely used due to its high sensitivity, specificity, and quantitative capability. For example, standardized qPCR systems have been established for WSSV detection, while multi-target real-time PCR assays have been developed for emerging viruses such as DIV1, enabling dynamic monitoring and early warning (Lee et al., 2023). Similarly, PCR and qPCR have demonstrated high reliability and reproducibility in detecting bacterial and microsporidian pathogens such as AHPND-causing Vibrio and EHP (Lou et al., 2025).

Recent developments have further improved the efficiency and practicality of molecular detection. Direct PCR techniques eliminate the need for nucleic acid extraction, thereby shortening detection time and reducing contamination risks. In addition, multiplex qPCR enables simultaneous detection of multiple pathogens. For instance, a five-plex qPCR assay can detect WSSV, IHHNV, DIV1, AHPND-causing Vibrio, and EHP in a single reaction, with a detection limit of 10 copies/μL and high specificity validated in large-scale studies (Lou et al., 2025). These advances significantly enhance detection efficiency in complex disease systems involving multiple pathogens.

4.3 Rapid detection and intelligent monitoring technologies

In recent years, shrimp disease detection technologies have shifted from centralized laboratory-based systems toward field-based and rapid diagnostic approaches. Given the rapid transmission and short response window of aquaculture diseases, technologies that enable on-site detection within a short time frame have become a major focus of research and application (Bohara et al., 2023). These methods emphasize simplicity, rapid response, and minimal equipment requirements, providing immediate support for on-site management decisions.

Among rapid molecular detection methods, isothermal amplification technologies show great potential. RPA, in particular, has attracted attention due to its low reaction temperature, fast processing time, and minimal equipment requirements. For example, RPA combined with lateral flow strip (RPA-LFS) can detect WSSV within approximately 30 minutes at 37 °C, with a detection sensitivity of around 20 copies and results consistent with qPCR. Similar approaches have been applied for detecting AHPND and EHP, with detection times of 20-35 minutes and sensitivity ranging from 10 to 100 copies. These techniques do not require complex thermal cycling equipment, making them suitable for field applications.

In terms of detection platforms and monitoring systems, current developments are moving toward integration and intelligence. Microfluidic chip technology enables the integration of nucleic acid amplification and signal detection into a single platform, allowing simultaneous detection of multiple pathogens. For example, microfluidic-based RPA systems can complete multi-pathogen detection within approximately 20 minutes (Li et al., 2023). In addition, CRISPR-based diagnostics combined with LAMP amplification can achieve highly sensitive detection within 30 minutes and support visual readouts (Major et al., 2023). Furthermore, biosensors, environmental DNA (eDNA) detection, and monitoring systems based on the Internet of Things (IoT) and artificial intelligence are increasingly being applied in aquaculture management (Figure 2) (Bohara et al., 2023; Zwetlana et al., 2023). By integrating water quality parameters, pathogen data, and behavioral information, these systems enable disease risk assessment and early warning. Overall, disease detection technologies are evolving from single-point diagnostics toward integrated systems featuring real-time monitoring, risk prediction, and precision intervention.

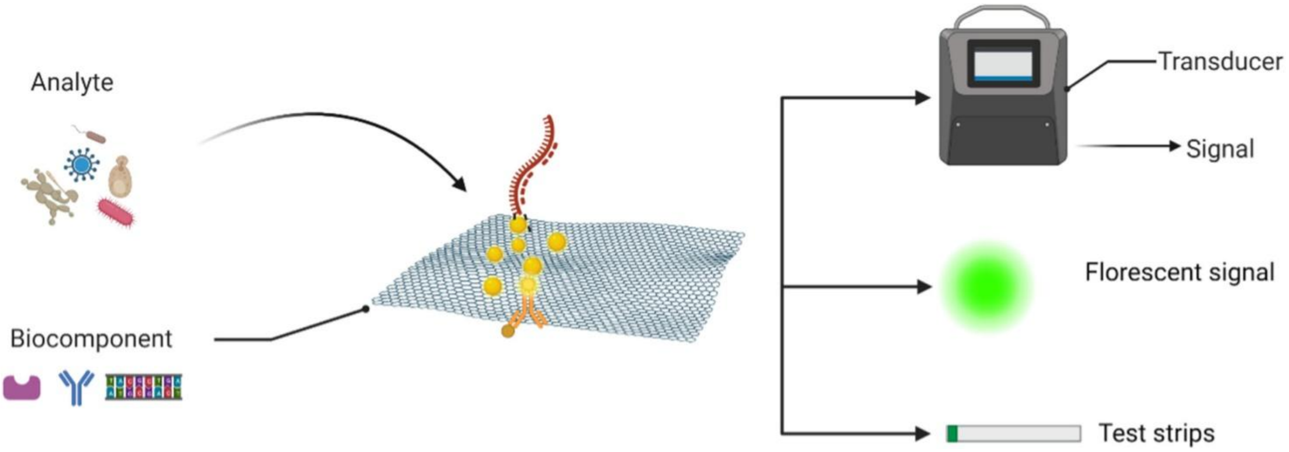

Figure 2 A chronological overview of disease diagnostic tool development (Adopted from Bohara et al., 2023)

5 Key Technologies for Disease Prevention and Control in Shrimp Aquaculture

5.1 Aquaculture management and ecological regulation

Aquaculture management and ecological regulation constitute the fundamental strategies for disease prevention and control in shrimp farming. Their core objective is to establish a stable aquaculture system characterized by low stress and low pathogen load through environmental optimization, standardized management practices, and reduced pathogen introduction risks. In recent years, disease control strategies have shifted from traditional drug-based treatments toward integrated management approaches centered on ecological regulation and biosecurity (Kumar et al., 2025). In this context, biosecurity systems based on specific pathogen-free (SPF) seedstock are widely regarded as a critical component of disease prevention. Strengthening quarantine measures, pathogen screening, and health assessments of broodstock and larvae can effectively reduce the introduction of major pathogens such as WSSV and AHPND at the source (Kumar et al., 2025).

During farming operations, appropriate stocking density remains a key factor in reducing disease incidence. Although high-density farming increases production per unit area, it also elevates contact frequency, water quality fluctuations, and chronic physiological stress, thereby facilitating pathogen transmission and disease outbreaks. Therefore, stocking density should be scientifically determined based on system carrying capacity, combined with adequate aeration, water exchange, and precision feeding management to maintain host health and reduce disease risks (Kumar et al., 2025). Water quality regulation is another critical component of ecological disease control. Maintaining parameters such as dissolved oxygen, pH, ammonia, and nitrite within optimal ranges helps alleviate physiological stress and suppress the proliferation of opportunistic pathogens such as Vibrio spp.

Sediment management also plays an important role in disease control. The accumulation of organic matter, including uneaten feed, feces, and dead algae, creates favorable conditions for pathogen proliferation, particularly benthic Vibrio and anaerobic metabolites that can negatively affect shrimp health. Measures such as pond sediment removal, the use of sediment conditioners, and the installation of settling systems can effectively reduce pathogen loads and improve system stability (Kumar et al., 2025). In recent years, ecological regulation has extended to the microbial level. Studies indicate that regulating water and gut microbiota composition can help maintain immune homeostasis and enhance disease resistance (Harpeni et al., 2024). In addition, comprehensive biosecurity practices—including water source disinfection, facility management, and personnel zoning—are essential for minimizing pathogen introduction and are integral to sustainable shrimp farming systems (Kumar et al., 2025).

5.2 Antibiotic alternatives and microbial regulation

Antibiotics have historically played a role in disease control in shrimp aquaculture; however, their overuse has led to increasing concerns regarding antimicrobial resistance, drug residues, and ecological risks. Consequently, antibiotic-free farming and alternative strategies have become major research and application priorities (Noman et al., 2024). In this context, environmentally friendly disease control approaches based on microbial regulation have rapidly developed, with probiotics, prebiotics, synbiotics, and biofloc technology emerging as key strategies.

Probiotic application is one of the most widely used microbial regulation methods. Beneficial microorganisms such as Bacillus, lactic acid bacteria, and Pseudomonas can be introduced into feed or water to inhibit pathogen colonization through competitive exclusion, competition for nutrients and adhesion sites, and the production of antimicrobial substances. Additionally, probiotics can modulate host immune responses and improve gut health (Tamilselvan and Raja, 2024). Studies have shown that probiotics enhance growth performance, survival rates, and stress resistance, thereby reducing reliance on antibiotics (Muthu et al., 2024). However, their effectiveness is influenced by factors such as strain selection, dosage, and environmental conditions, highlighting the need for standardized and optimized application strategies (Noman et al., 2024).

In addition to probiotics, prebiotics and synbiotics also play important roles in microbial regulation. Prebiotics promote the growth and colonization of beneficial microbiota, thereby enhancing gut microbial stability, while synbiotics combine the synergistic effects of probiotics and prebiotics to further improve host immunity and metabolic functions (Noman et al., 2024). Biofloc technology (BFT) represents a system-level application of microbial regulation. By adjusting the carbon-to-nitrogen ratio, BFT promotes the growth of heterotrophic microorganisms that convert nitrogenous wastes into microbial biomass, thereby improving water quality and reducing toxic compounds (Harpeni et al., 2024). The resulting bioflocs also serve as supplementary nutrition and help stabilize microbial communities, suppressing pathogen proliferation. Studies have demonstrated that microbial consortia derived from native microbiota can effectively reduce AHPND incidence and improve shrimp growth performance (Figure 3) (Guo et al., 2023). Microbial regulation strategies are shifting disease control approaches from pathogen suppression to ecological balance restoration.

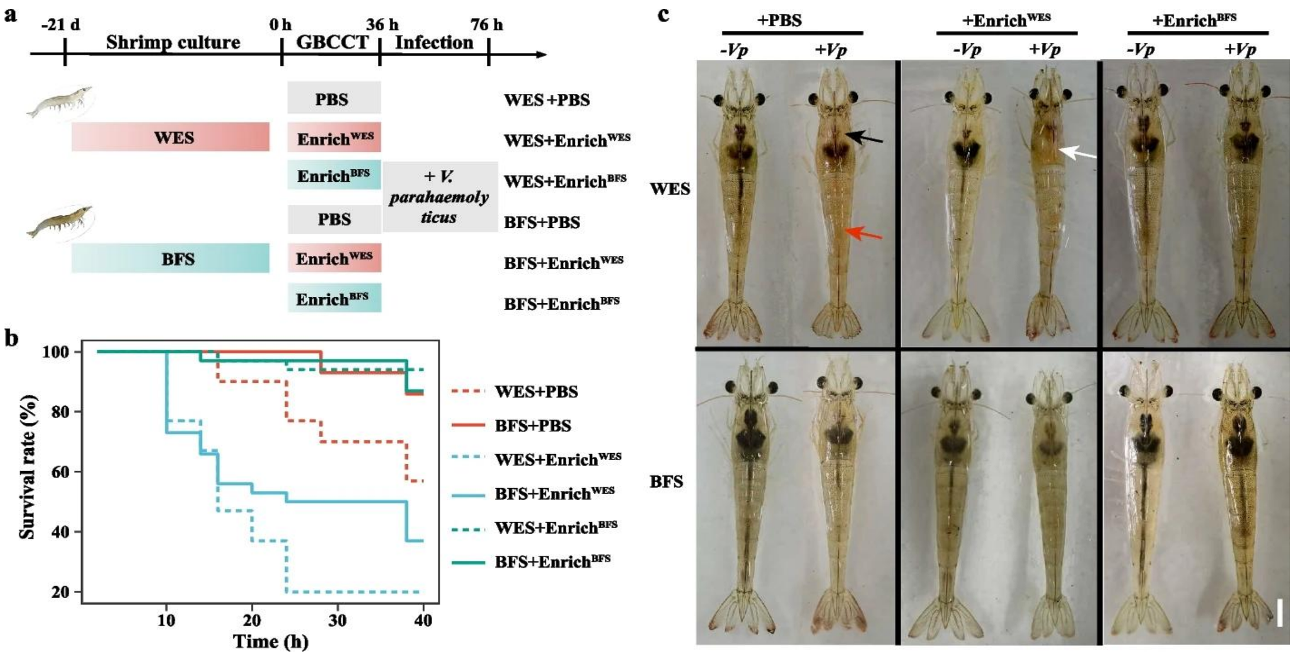

Figure 3 The Vibrio infection resistance, and phenotypic characteristics of shrimp after cross-transplantation of bacterial consortia enriched from WES and BFS shrimp (Adopted from Guo et al., 2023)

Image caption: (a) Schematic diagram of the experimental procedure. The bacterial consortia were obtained from the shrimp cultured in the WES and BFS for 21 days, and the bacterial consortia were cross-transplanted to WES and BFS shrimp. After 36h of cross-transplantation, the shrimp that received PBS and bacterial consortia were infected by the pathogenic Vibrio parahaemolyticus. (b) The effects of cross-transplantation on the shrimp survival curves after infection; c Phenotypic characteristics of shrimp after infection. Black, white, and red arrows indicate the stomach, hepatopancreas, and gut of shrimp in (c), respectively. Bar=1 cm in (c); WES, Water exchange system; BFS, Biofloc system; PBS, Phosphatic buffer solution; EnrichWES, Bacterial consortium obtained from WES shrimp; EnrichBFS, Bacterial consortium obtained from BFS shrimp; -Vp, non-Vibrio infection; + Vp, Vibrio infection (Adopted from Guo et al., 2023)

5.3 Immunoregulation and genetic breeding

Due to the absence of a typical adaptive immune system in shrimp, conventional vaccination strategies are limited in their ability to provide long-term protection. Therefore, enhancing innate immunity and improving host resistance through genetic approaches have become key strategies for long-term disease control. Immunoregulation techniques aim to enhance host resistance through immune priming and functional additives. Common immunostimulants include polysaccharides derived from plants, algae, and microorganisms, as well as vitamins and minerals. These compounds can activate pattern recognition receptors, regulate signaling pathways such as NF-κB, and upregulate antimicrobial peptide expression, thereby improving resistance to WSSV and Vibrio infections.

In recent years, the concept of “trained immunity” has gained increasing attention in shrimp health management. Studies suggest that early stimulation or nutritional interventions can induce an enhanced innate immune state, thereby improving resistance to subsequent infections. Furthermore, broodstock nutrition and epigenetic regulation may influence offspring resistance, providing new perspectives for disease prevention (Wikumpriya et al., 2023). Mechanisms such as DNA methylation, histone modification, and non-coding RNA regulation are believed to play roles in immune gene expression and transgenerational resistance (Wikumpriya et al., 2023).

In terms of genetic breeding, the development of disease-resistant strains offers a long-term and stable solution for disease control. Traditional selective breeding has already achieved progress in certain cultured populations. With advances in molecular technologies, approaches such as marker-assisted selection (MAS), genomic selection, and genome-wide association studies (GWAS) are increasingly applied to elucidate disease resistance traits. Studies indicate that resistance to WSSV in Litopenaeus vannamei exhibits relatively high heritability, demonstrating the feasibility of genetic improvement (Nguyen, 2024). In addition, emerging technologies such as RNA interference and CRISPR/Cas provide new tools for understanding disease resistance mechanisms and enabling precise genetic improvement. However, their practical application must consider ecological safety, regulatory frameworks, and cost factors (Wikumpriya et al., 2023). Overall, immunoregulation and genetic breeding are driving disease control strategies toward a host-centered approach focused on enhancing resistance.

6 Typical Prevention and Control Models and Practical Applications

6.1 Green ecological farming model

Eco-friendly shrimp aquaculture models achieve disease control by stabilizing pond ecosystems, reducing pathogen pressure, and minimizing chemical inputs. Integrated multi-trophic aquaculture (IMTA) and polyculture systems combine shrimp with fish, shellfish, and/or seaweeds, enabling nutrient recycling, improving water quality, and reducing the accumulation of opportunistic pathogens, thereby enhancing system stability (Arriesgado et al., 2025; Uddin et al., 2025). Studies have shown that IMTA systems in China exhibit diverse combinations, such as shrimp–crab, fish, sea cucumber, jellyfish, and shellfish, which can be optimized according to local ecological conditions. These systems not only improve resource utilization efficiency and reduce waste discharge but also significantly enhance economic returns compared to monoculture systems, while lowering disease risks and environmental pressure (Uddin et al., 2025). Furthermore, IMTA effectively removes excess nutrients, balances nutrient budgets, and reduces carbon emissions, making it an important approach for achieving both environmental and economic sustainability (Uddin et al., 2025).

Polyculture systems also serve as effective ecological disease control strategies. For example, a fish–shrimp co-culture model developed in China introduces specific fish species that actively consume dead or moribund shrimp, thereby interrupting the transmission of white spot syndrome virus (WSSV) within ponds. This approach does not require complex biosecurity infrastructure, is easy to implement, and is suitable for small- and medium-scale farmers. It has been widely adopted in China, effectively reducing WSS-related losses while increasing overall production. In addition, green water systems, biofloc technology, and the application of probiotics and prebiotics are considered effective alternatives for controlling bacterial diseases such as vibriosis. These approaches not only improve water quality but also promote growth, enhance stress resistance and disease resistance, and reduce environmental pollution (Noman et al., 2024; Arriesgado et al., 2025; Kumar et al., 2025).

6.2 Industrialized and recirculating aquaculture systems (RAS)

At the other end of the intensification spectrum, industrialized aquaculture and recirculating aquaculture systems (RAS) achieve disease control through enhanced biosecurity and environmental regulation. The future of sustainable shrimp farming lies in the development of efficient, biosecure systems based on SPF seedstock and genetically improved strains, combined with strict pathogen monitoring and quarantine measures throughout the production cycle. RAS and inland closed systems reduce reliance on open water sources and minimize contact with wild hosts. At the same time, indoor environmental control stabilizes key parameters such as temperature and salinity, thereby reducing pathogen exposure and disease risks associated with climate variability (Kumar et al., 2025). Although RAS offers advantages such as water conservation, high productivity, and reduced ecological impacts (e.g., habitat destruction, eutrophication, and escape events), its high energy consumption and capital costs limit its widespread adoption, particularly in developing countries.

Technological innovations are improving the sustainability and disease resistance of intensive aquaculture systems. For example, a high-density, low-salinity culture system for Litopenaeus vannamei integrating zero water discharge (ZWD) and RAS has demonstrated the ability to maintain good water quality at stocking densities up to 1000 individuals/m³, with optimal survival and feed conversion efficiency achieved at 500 individuals/m³, indicating strong potential for urbanized inland aquaculture. Membrane-based RAS (MRAS), incorporating microfiltration, ultrafiltration, and membrane bioreactors, can effectively remove suspended solids, toxic substances, pathogens, and excess nutrients, thereby improving water reuse efficiency and reducing environmental impacts. However, membrane fouling, energy consumption, and operational costs remain key challenges (Widiasa et al., 2023). In addition, maintaining the stability of filtration systems is critical; for instance, studies have shown that certain antimicrobial agents can suppress Vibrio without affecting nitrifying bacteria or shrimp health, highlighting the need for disease control strategies compatible with RAS systems.

6.3 Successful cases and integrated control strategies

Sustainable disease control increasingly relies on integrated management approaches. Case studies from Asia indicate that repeated outbreaks of WSSV and AHPND have driven a transition from traditional flow-through pond systems to more closed and controlled systems. By incorporating water storage ponds, wastewater treatment systems, reduced water exchange, and RAS components, higher levels of biosecurity can be achieved (Kumar et al., 2025). In China, the widespread adoption of IMTA and polyculture systems has not only increased production but also reduced wastewater treatment costs and alleviated disease and environmental pressures, demonstrating both economic and ecological benefits (Uddin et al., 2025). Similarly, an IMTA trial in the Philippines showed that co-culturing tiger shrimp with fish, seaweed, and shellfish reduced pathogen loads, prevented AHPND occurrence, lowered WSS outbreaks, and significantly improved total production, net income, and return on investment (Arriesgado et al., 2025). These findings highlight the practical value of IMTA in both disease control and economic performance.

At the technical and management levels, integrated disease control strategies are equally critical. Studies emphasize the need to combine SPF/SPR seedstock, biosecurity measures, molecular diagnostics, and antibiotic-free approaches such as probiotics, immunostimulants, nanotechnology, and biological control methods (Bondad-Reantaso et al., 2023; Noman et al., 2024). Aquaculture systems based on water recirculation and reuse, combined with non-antibiotic antimicrobial strategies, are considered effective pathways to reduce antimicrobial resistance risks and achieve sustainability goals (Bondad-Reantaso et al., 2023; Natrah et al., 2025). In addition, sensor-based automated systems can regulate the application of probiotics and water conditioners based on real-time water quality and microbial data, thereby reducing organic load and pathogen levels, improving water quality, and lowering labor costs (Kumar et al., 2025).

7 Challenges and Future Issues

7.1 Pathogen variation and emerging disease risks

With the continuous expansion of shrimp aquaculture and the increasing intensity of high-density farming and transregional trade, pathogen evolution and emerging disease risks have become major challenges to the sustainable development of the industry. Previous studies indicate that shrimp diseases are not static but represent a dynamic system that evolves under the combined influences of industry expansion, ecological disturbances, and global trade. Viral pathogens, in particular, exhibit high mutation rates and transmission efficiency, and under changing host and environmental conditions, they tend to show increased virulence, expanded host range, and cross-regional dissemination. Since the 20th century, major viral diseases such as white spot syndrome virus (WSSV), yellow head virus (YHV), infectious myonecrosis virus (IMNV), and the recently emerging DIV1 have caused repeated outbreaks and sustained impacts across multiple aquaculture regions. Continuous emergence of new viruses and ongoing evolution of existing ones impose persistent challenges on current diagnostic systems and control strategies.

In this context, the transboundary movement of seedstock and live aquatic products, expansion of aquaculture into new regions, and environmental fluctuations driven by climate change create favorable conditions for pathogen spread and adaptation. Meanwhile, emerging bacterial and microsporidian diseases further increase the complexity of the disease spectrum. Pathogens such as AHPND-causing Vibrio and Enterocytozoon hepatopenaei (EHP) often occur as co-infections, leading to higher mortality and greater challenges in diagnosis and control. Field investigations indicate that multi-pathogen coexistence and alternating outbreaks are common in aquaculture systems. In addition, intensive farming practices, antibiotic selection pressure, and rising water temperatures may accelerate pathogen adaptation and evolution (Nguyen, 2024). Therefore, reliance on single-pathogen-based or fixed control strategies is no longer sufficient. Strengthening molecular epidemiological surveillance, pathogen tracing, and cross-regional early warning systems is essential to improve the identification and response capacity for emerging and evolving pathogens (Bhassu et al., 2024).

7.2 Antibiotic misuse and antimicrobial resistance

Antibiotics have long been used in shrimp aquaculture for disease prevention and treatment, and in some regions even for growth promotion. Although this practice may alleviate disease pressure in the short term, it has led to significant concerns regarding antimicrobial resistance (AMR), drug residues, and ecological risks (Bondad-Reantaso et al., 2023; Devadas et al., 2023). Studies have shown that various antibiotics, including fluoroquinolones, tetracyclines, and sulfonamides, are still used in shrimp farming, with some of these substances restricted or banned in food-producing animals. The frequent and often suboptimal use of these antibiotics increases the selection pressure for resistant bacteria and resistance genes within aquaculture systems (Devadas et al., 2023).

Additionally, aquaculture effluents interact with pollutants from urban, livestock, and medical sources, turning aquaculture environments into hotspots for the dissemination and exchange of resistance genes. This phenomenon reflects a typical “One Health” issue, where aquatic environments, animal health, and human health are closely interconnected (Natrah et al., 2025). The rise of antimicrobial resistance not only reduces treatment efficacy but also complicates disease management. For instance, Vibrio strains associated with AHPND may harbor multiple resistance genes, thereby limiting the effectiveness of antimicrobial treatments (Devadas et al., 2023). Moreover, antibiotic use disrupts aquatic and gut microbiota, suppresses beneficial bacteria, and promotes opportunistic pathogens, creating a reinforcing cycle of disease pressure and drug dependence. Therefore, integrated strategies—including strengthened biosecurity, adoption of alternative technologies, monitoring of residues and resistance, and farmer training—are essential to reduce antibiotic reliance and mitigate associated risks (Bondad-Reantaso et al., 2023; Natrah et al., 2025).

7.3 Insufficient technology transfer and standardization

Despite significant advances in shrimp disease prevention technologies—such as SPF/SPR seedstock, molecular diagnostics, ecological aquaculture, and genomic approaches—their application at the production level remains limited. In many aquaculture regions, insufficient laboratory capacity, limited infrastructure, and a shortage of skilled personnel hinder the effective translation of advanced technologies into practical tools for farmers (Zwetlana et al., 2023; Bhassu et al., 2024; Nguyen, 2024). Furthermore, the predominance of small- and medium-scale farms, coupled with limited financial and technical resources, often leads farmers to rely on low-cost and experience-based management practices rather than investing in high-standard biosecurity and diagnostic systems. Studies indicate that barriers to the transition toward sustainable aquaculture are not solely technological but also involve institutional, financial, informational, and supply chain constraints.

In addition, insufficient technology dissemination is closely linked to gaps in training and standardization systems. In many regions, farmers lack adequate training in pathogen detection, risk assessment, and standardized management, limiting the effectiveness of available technologies (Zwetlana et al., 2023). The absence of unified standards for seedstock management, water quality control, and antimicrobial use further restricts data comparability and knowledge transfer across regions (Devadas et al., 2023). Even advanced technologies such as genetic breeding and genome editing face challenges related to ecological safety, regulatory requirements, and public acceptance (Nguyen, 2024). Therefore, promoting technology standardization, regional adaptation, and demonstration-based dissemination is essential for transforming research outcomes into practical productivity gains in shrimp aquaculture.

8 Future Trends and Perspectives

Future strategies for disease prevention and control in shrimp aquaculture are gradually moving away from reliance on antibiotics toward integrated approaches centered on ecological sustainability and multi-target regulation. These approaches aim to enhance host resistance while reducing pathogen pressure. Emerging technologies, including nanomaterials, plant-derived bioactive compounds, algal extracts, probiotics, prebiotics, synbiotics, biofilm-based vaccines, bacteriophage therapy, quorum sensing inhibition, RNA interference, and DNA/physicochemical biosensors, have shown great potential as alternatives to traditional chemical treatments. These innovations can maintain productivity while minimizing the risk of antimicrobial resistance. In addition, immunostimulants and antiviral compounds derived from plants, animals, and synthetic sources, when combined with strict disinfection measures, can effectively and safely enhance innate immunity in shrimp, particularly for the control of WSSV. Epigenetic regulation and "trained immunity" represent promising research frontiers, offering the potential to achieve heritable or long-term disease resistance through modulation of immune gene expression. Furthermore, microbiome-based engineering strategies, such as customized probiotics, synthetic microbial consortia, and fecal microbiota transplantation, are expected to become key components of future disease control, although their ecological adaptability, safety, and resilience to climate change require further investigation.

With the rapid development of the Internet of Things (IoT), artificial intelligence (AI), and their integration (AIoT), shrimp health management is increasingly shifting toward precision aquaculture. Sensor- and microcontroller-based monitoring systems can now provide real-time measurements of key water quality parameters, including temperature, pH, salinity, turbidity, total dissolved solids (TDS), and electrical conductivity. These systems enable remote management, anomaly detection, and automated regulation (e.g., aeration and chemical dosing) through cloud platforms and mobile applications. Machine learning models, including regression and classification algorithms, have been successfully applied to predict water quality changes and evaluate production performance with high accuracy, allowing early intervention to reduce mortality and optimize yields. Studies indicate that the integration of AIoT with precision aquaculture enables intelligent decision-making in feed management, disease monitoring, biomass estimation, and environmental regulation through the combination of sensor data, AI analytics, and remote sensing technologies. However, high investment costs, data privacy concerns, and limitations in model generalization remain key challenges. Additionally, emerging "smart dosing systems" can automatically apply probiotics and water quality regulators based on microbial and environmental data, effectively reducing organic load and pathogen levels in biofloc systems while lowering labor costs and improving sustainability.

Overall, existing studies suggest that future shrimp disease control will evolve toward comprehensive systems centered on biosecurity, integrating host, pathogen, environmental, and management factors. Sustainable shrimp aquaculture will depend on high-level biosecure facilities, the use of SPF seedstock and genetically improved disease-resistant strains, and the implementation of efficient pathogen monitoring systems and rapid diagnostic technologies, such as high-throughput sequencing, CRISPR-based detection, and culture-independent biosensors. Current research emphasizes the need to establish dynamic, risk-based management frameworks that integrate physical, biological, and operational biosecurity measures with emerging technologies and multi-stakeholder collaboration. Key future research directions include microbiome-based disease regulation, genetic and epigenetic improvement of disease resistance, detection technologies for emerging pathogens, and the development of climate-resilient aquaculture systems, such as IMTA, RAS, and hybrid models. The integration of green control technologies, precision monitoring, genetic breeding, epigenetic regulation, and comprehensive biosecurity systems will facilitate the transition of shrimp aquaculture from traditional "reactive treatment" to a "prevention-oriented and system-regulated" health management model, thereby ensuring long-term sustainability and contributing to global food security.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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