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Challenges and opportunities in developing vaccines for the prevention of acute hepatopancreatic necrosis disease in shrimp

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Abstract

Acute hepatopancreatic necrosis disease (AHPND) is one of the most devastating bacterial diseases affecting shrimp aquaculture, causing severe economic losses worldwide. Traditionally, shrimp have been considered incapable of developing adaptive immune responses because they lack the classical antibody-mediated immune system found in vertebrates. However, accumulating evidence suggests that shrimp and other invertebrates possess forms of immune priming and specific innate immunity that can provide enhanced protection against repeated pathogen exposure. These findings have renewed interest in the development of vaccine-like strategies for disease prevention in shrimp farming. The increasing global restrictions on antibiotic use in aquaculture have further accelerated research into immunostimulants, oral vaccines, recombinant antigens, nucleic acid-based approaches, and other innovative prophylactic strategies against bacterial pathogens, including the causative agents of AHPND. Nevertheless, significant biological and technical challenges remain, including the limited understanding of immune memory mechanisms, antigen delivery systems, immune response durability, and large-scale field application. This review summarizes current knowledge of shrimp immune mechanisms relevant to AHPND prevention, critically evaluates existing vaccine development strategies and experimental evidence, discusses the role of immune-related molecules such as Dscam and innate immune priming, and highlights the major challenges and future opportunities for developing effective and commercially viable vaccination approaches for sustainable shrimp aquaculture.

Keywords: Acute hepatopancreatic necrosis disease (AHPND), Shrimp immunity, Innate immune memory, Immune priming, Dscam, Vibrio parahaemolyticus, Shrimp vaccine, Sustainable aquaculture

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Introduction

The development and expansion of aquaculture activities, especially shrimp farming, in recent years have been accompanied by an increase in the incidence and prevalence of various diseases. These diseases usually cause heavy losses to the shrimp aquaculture industry and have led to a significant decrease in the performance and productivity of farms. One of the most important bacterial diseases in shrimp is acute hepatopancreatic necrosis disease, which is known as one of the main factors for reduced production in this industry (Huang *et al.*, 2025). The use of antibiotics in aquaculture has been banned or strictly limited in many countries due to their potential adverse effects on human and environmental aquatic health. Furthermore, the emergence of antibiotic-resistant strains has increased concerns and intensified restrictions on their consumption. Repeated and incorrect use of various antibiotics in past years has led to the emergence of multi-resistant pathogens and has reduced the effectiveness of antibiotic treatments in controlling bacterial infections. Hence, the development of alternative methods, such as the use of vaccines to strengthen the immune system of aquatic animals, especially in shrimp farming, has attracted the attention of researchers (Li and Lin, 2025).

Since the beginning of shrimp farming activities, various types of infectious diseases have emerged in cultured populations. The most common pathogens include viruses and bacteria, and in some cases, fungal infections also play a role, which cause damage, especially in the larval and shrimp growth stages. The continuous increase in aquaculture activities, especially shrimp farming, along with other stressors such as fluctuations in water temperature and salinity, has exacerbated the incidence and severity of these diseases. Estimates show that about 60 percent of losses in cultured shrimp production are caused by viral infections, including white spot syndrome virus, while about 20 percent of losses are attributed to bacterial factors, mainly *Vibrio* species (Bhassu *et al.*, 2024).

Vibriosis in shrimp farming is recognized as a constant threat. *Vibrio harveyi* is one of the most important shrimp pathogens that can cause mass mortality of *Penaeidae* shrimp in hatcheries and farming ponds. Apart from that, *V. parahaemolyticus* causes acute hepatopancreatic necrosis (AHPND) in shrimp, a disease that has significantly destabilized the shrimp industry for nearly a decade. *V. harveyi* strains with multiple resistance to streptomycin, erythromycin, and cotrimoxazole cause mass mortality in shrimp larvae (Vandeputte *et al.*, 2024).

Vibriosis, as a constant threat in shrimp farming, has caused a wide range of problems in shrimp, from growth retardation to sporadic mortality and finally mass mortality at different stages of the shrimp life cycle (Kumar *et al.*, 2026). *Vibrio* species are found everywhere in marine aquaculture systems and marine environments. This group of bacteria has its own niche in environments such as symbionts and plays a role in the marine organic carbon cycle. Among the known *Vibrio* species, *V. harveyi* and *V. parahaemolyticus* are important pathogens associated with vibriosis disease in the midgut and digestive tract and hepatopancreas in shrimp (Pinos-Tamayo *et al.*, 2026). These pathogens have infected shrimp culture from the very early days of shrimp farming. In addition, *V. harveyi* infection can appear in various shrimp diseases, including Bright-red syndrome, bacterial white tail disease, luminous vibriosis, and *Bolitas nigricans* syndrome. Another important *Vibrio* species that infects shrimp is *V. parahaemolyticus*. This disease has been linked to acute hepatopancreatic necrosis disease in shrimp (Fadel *et al.*, 2025). AHPND created a serious threat to the shrimp industry globally, resulting in annual losses of $1 billion (Guzman, 2022). This disease was first reported in southern China in 2009. In a relatively short period, this disease was reported in the region of Southeast Asia, Mexico, and the United States of America and quickly became a worldwide concern. Other *Vibrio* species that can cause vibriosis in shrimp include *V. alginolyticus*, *V. angullarium*, and *V. damsela*. To date, vibriosis has usually occurred in shrimp farming. Furthermore, the occurrence of horizontal gene transfer between *Vibrio* species is also concerning because pathogenic and antibiotic-resistant traits can be shared among closely related species (Soto-Rodriguez *et al.*, 2024; Kumar *et al.*, 2024).

Acute hepatopancreatic necrosis disease (AHPND)

Acute hepatopancreatic necrosis disease, previously known as early mortality syndrome, is an emerging disease that has caused significant economic losses to the shrimp farming industry. This disease can cause sudden death and mass mortality of shrimp and can be observed at 30–35 days after stocking shrimp (Hassan *et al.*, 2025). The main causative agent of this disease is the bacterium *Vibrio parahaemolyticus*, which is a Gram-negative rod-shaped bacterium. This bacterium possesses the pVAI plasmid, which produces lethal binary toxins Pir A/Pir B, causing rapid death of infected shrimp. This plasmid causes disease in the midgut, digestive tract, and hepatopancreas in shrimp through the synthesis of these toxins (Wang *et al.*, 2026). The pathogenic bacterium can be more widely present in hatcheries and farming ponds. Based on recent studies, environmental factors such as temperature, salinity, and dissolved oxygen can be effective in the survival, establishment, and proliferation of this bacterium (Xu *et al.*, 2025).

Shrimp immune system

The defense mechanism in crustaceans includes two types of innate and adaptive immune systems. Innate immunity is based on responses that the host shows upon the first encounter with a pathogen and depends on species-specific and genetic characteristics, whereas adaptive immunity includes responses that occur after the initial encounter with an invading pathogen or antigen and internal metabolic materials (Bouallegui, 2021; Xin and Zhang, 2023). This defense mechanism includes cellular and humoral immune mechanisms. Cellular immune responses in crustaceans include the activity and function of various types of cells present in the crustacean hemolymph. Humoral responses are actually a type of cellular response that is accompanied by cell secretions with bactericidal properties and inhibition of bacterial growth. Both humoral and cellular defense mechanisms cause the elimination of invading pathogens through a series of coordinated and simultaneous activities (Roy *et al.*, 2025).

Shrimp lack a complete adaptive immune system and mainly rely on innate immunity. Although initial findings regarding the existence of a type of adaptive immune system in invertebrates, including shrimp, have made vaccination in these organisms seem more promising. New evidence shows that innate immunity can be trained and customized. This process, known as "trained immunity", allows for the creation of a type of immune memory that can protect the body in subsequent encounters (Hsu *et al.*, 2025). For this reason, producing a vaccine against common diseases like vibriosis among shrimp is a very promising path. The idea of specific immunity in insects and crustaceans was proposed to explain observations of increased phagocytic activity in arthropod hemocytes after previous exposure to foreign antigens. Although arthropod hemocytes were previously known to express pattern recognition proteins (PRP), which differentiated between self and non-self-molecules (Madsari *et al.*, 2022). The first evidence that Dscam might be involved in this phagocytic mechanism was discovered only more than two decades later (Ng *et al.*, 2014).

Hemocytes are the main mediators of the crustacean cellular immune response, which act on various pattern recognition receptors, effective functions, and dependent signalling pathways. The host immune response, which includes initial non-self recognition, phagocytosis, encapsulation, melanization, cytotoxicity, and cell-cell communication, is heavily dependent on hemocytes (Cui *et al.*, 2022). Most crustacean hemocytes can be classified into three categories: hyaline cells (HC), semi-granular cells (SGC), and granular cells (GC). Hyaline cells are responsible for phagocytosis, while semi-granular cells are involved in encapsulation, initial non-self recognition, melanization, and coagulation in some species, and granular cells are the site of storage and initial release of the proPO system and also have the functions of melanization, cytotoxic reaction, and production and secretion of antimicrobial peptides (Söderhäll *et al.*, 2025). SGC and GC hemocytes undergo rapid degranulation reactions in the presence of pathogen-associated molecular patterns (PAMPS) and release a set of powerful immune effector molecules into the circulation in the vicinity of stimulating PAMPs, which perhaps it is not surprising that zymogen pro-phenoloxidase (proPO) has been studied the most (Xu *et al.*, 2026). In crustaceans, coagulation and clotting is another important immune response that, in case of injury, immediately forms clots from blood components to prevent the loss of hemolymph, and transglutaminase (Tgase) plays an important role in this activity. In addition to immediate immune responses, hemocytes are also important suppliers of various antimicrobial peptides, lectins, proteinase inhibitors, and opsonins such as peroxinectin cell adhesion protein (Soni *et al.*, 2026).

Immune system enzymes

Various immune enzymes, including phenoloxidase (PO), acid phosphatase (ACP), alkaline phosphatase (ALP), and lysozyme (LSZ), are generally recognized as indicators for assessing the immune status and disease resistance of shrimp (Liang *et al.*, 2020). ACP and ALP consist of various types of phosphomonoesterases that are crucial for the crustacean immune system. Furthermore, ACP is an important component of phagocytic lysosomes and is involved in the phagocytosis and encapsulation of hemocytes. Phagocytic lysosomes have antibacterial roles by releasing ACP. ALP is a type of phosphomonoesterase that helps in detoxification and phagocytosis and in the digestion and absorption of many nutrients. Lysozyme is a part of the shrimp innate immune system that acts as an antibacterial protein and breaks down mucopolysaccharides, which are the main components of the bacterial cell wall, and kills pathogens (Liang *et al.*, 2020). In many invertebrates, PO represents the host's vital defense response. PO is the final enzyme in the pro-PO activation system and plays a role in host defense reactions such as wound repair, cytotoxicity, and phagocytosis.

Shrimp antioxidant system

Antioxidant activities are an indicator of the antioxidant status and oxidative stress in aquatic animals. When the production of reactive oxygen species (ROS) increases, living organisms are able to activate a set of antioxidant defense systems such as superoxide dismutase (SOD), catalase (CAT), glutathione S-transferase (GST), and glutathione peroxidase (GSH-PX) for the purpose of detoxification, preventing or repairing oxidative damage (Liang *et al.*, 2020). SOD is a molecular biomarker for assessing the oxidative stress status of aquatic organisms because it catalyzes the change of superoxide anions to hydrogen peroxide and molecular oxygen and forms a first-line enzymatic antioxidant defense system. The antioxidant enzymes SOD and CAT are responsible for eliminating superoxide radicals and play a role in protective mechanisms in tissue damage following oxidative process and phagocytosis. GSH-PX can eliminate lipid peroxides caused by reactive oxygen species and OH, maintaining the integrity of the cell membrane and protecting against pathogens. GSH acts with glutathione peroxidase in reducing hydrogen peroxide to water, consequently protecting the integrity of the red blood cell membrane (Chen *et al.*, 2025).

Down syndrome cell adhesion molecule (Dscam)

Specific immune response in invertebrates involves a group of molecules called Dscam (Down Syndrome Cell Adhesion Molecule), a member of the immunoglobulin superfamily that plays a key role in the alternative adaptive immune system (Li *et al.*, 2018). Li *et al.* (2022) demonstrated that the intracellular domain (ICD) of Dscam functions as a signaling molecule that translocates to the nucleus following bacterial infection, where it regulates the expression of genes involved in immune responses and hemocytes proliferation. Their findings highlighted the importance of Dscam-mediated signaling in enhancing antibacterial defense mechanisms. Similarly, Li *et al.* (2018) showed that Dscam generates pathogen-specific isoforms through alternative splicing, enabling selective recognition of invading microorganisms. They further demonstrated that soluble Dscam acts as an opsonin, promoting pathogen binding and facilitating phagocytosis by immune cells. This specific immune response has also been reported in other invertebrates such as the fruit fly (*Drosophila melanogaster*), honey bee (*Bombus terrestris*), and mosquito (*Anopheles gambiae*) (Hizawa *et al.*, 2024).

In this regard, studies conducted on shrimp indicate the immunogenicity of factors such as inactivated virus, recombinant viral protein, and inactivated bacteria in protecting shrimp from mortality by related pathogens. The results of these studies showed that Dscam, as a member of the immunoglobulin superfamily (IgSF), plays an important role in the shrimp immune system (Li *et al.*, 2025). By alternative splicing, a group of Dscam isoforms induced against specific pathogens after exposure to the pathogen acted similar to PRRs (pattern recognition receptors) of the insect immune system. Nevertheless, Dscam isoforms were identified in the hemocytes of vaccinated and non-vaccinated shrimp. Further analysis showed that the specific immunity of shrimp against WSSV is more important because it helps to identify the specific pathogen (Patnaik *et al.*, 2024). The same phenomenon has been reported in *P. monodon*. Finally, pathogens will be eliminated through the phagocytic activity of specific hemocytes. Evidence for the role of phagocytosis in viral clearance has been reported in Kuruma shrimp (*P. japonicus*). These findings led to several independent studies on the immunization of shrimp against WSSV (Zhang *et al.*, 2025).

Although the mechanisms that underlie these phenomena are not yet well understood, if an invertebrate host can identify a number of different pathogens with specific characteristics, it likely requires a specific pathogen receptor that is capable of high diversity. In arthropods, these characteristics are found in the Down Syndrome Cell Adhesion Molecule (Dscam), which shows very high diversity and is created from a single-copy gene through alternative splicing. However, if Dscam is to successfully mimic the adaptive response of mammals, it should be expected that the population of arthropod Dscam isoforms changes in response to invading microorganisms and Dscam isoforms should also act as specific pathogen recognition receptors (Wan *et al.*, 2019). Although specific Dscam isoforms induced by pathogens have been identified in many arthropod species, the precise mechanism of the production of these isoforms in response to pathogen exposure is not yet fully known. The processes that regulate the selection of isoforms specifically are very complex and likely involve the competition of secondary structure of RNA, the influence of signalling pathway regulators, especially serine-arginine (SR) rich proteins and RNA knots, as well as the involvement of local RNA splicing networks (Shi *et al.*, 2024).

Recent studies have shown that in the face of various bacteria and viruses, the composition of Dscam isoforms changes in parallel with the pathogen; in such a way that some isoforms are produced only after contact with a specific pathogen, and this indicates their role in a type of quasi-adaptive specific immunity. However, it is still not clear which cellular signals or transmitters induce this selection. Initial evidence includes the activities of RNA containing different effects in splicing diversity and different phases of immunity, but a large part of these mechanisms remains unknown and requires more applied research (Amatul-Samahah *et al.*, 2020).

Vaccination development studies for shrimp

The development of commercial vaccines is accompanied by many challenges, including the unique immune systems of shrimp that are not yet fully understood, as well as the need for sensitive methods for vaccine delivery that can create a strong and effective immune response. On the other hand, recently, novel methods such as oral vaccination with harmless bacteria that transfer antigen genes to host cells have also shown significant protective effects in increasing shrimp resistance to viruses (Elbahnaswy *et al.*, 2025). Therefore, the most important next step in completing the vaccination capability against vibriosis is conducting comprehensive and multifaceted studies at the molecular, cellular, and environmental levels to be able to discover trained immune characteristics in shrimp and use them for designing safe and effective vaccines. This report reviews research that has been done in line with the development of a vaccine against acute hepatopancreatic necrosis in shrimp and its potential.

Research in the field of shrimp vaccine production began in the late 1980s. In those years, pathogens were inactivated using heat or formalin for vaccine production. These methods are still widely used in recent studies to produce inactivated *Vibrio* cells. The methods are still very relevant because they are not only simple and cheap but also lead to the production of a stable vaccine. In general, there are various types of vaccines, including inactivated, attenuated, live, subunit recombinant, DNA, and synthetic peptide vaccines (Singh *et al.*, 2024). All these vaccines are essentially a biological preparation containing antigens that resemble a pathogen. The antigen stimulates the body's immune system to identify the pathogen so that the immune system can easily destroy the homologous microorganism. Various studies have used the inactivation of the whole cell for immunogenicity. Although *V. harveyi* biofilms and lipopolysaccharides of *V. alginolyticus* have been used for shrimp vaccination, isolating these components from pathogens requires a complex and time-consuming preparation step. It has been shown that these materials improve the protection against AHPND in the treatment group compared to the control group (Amatul-Samahah *et al.*, 2020).

Another field test was conducted by Ray *et al.* (2017). Post-larvae of *P. monodon* were stocked at different densities (low, medium, and high) in three different farms. The inactivated vaccine was administered through feeding. Shrimp feed was coated with formalin-killed *V. anguillarium* cells, and shrimp were fed for a period of about 140 days during the breeding period for two consecutive days per week until harvest. The water quality parameters of the culture ponds were kept in the optimal range to prevent significant fluctuations that cause stress to the shrimp. It was found that the level of total hemocytes count and phenoloxidase activity in adult shrimp receiving vaccine-coated feed was significantly higher than shrimp receiving the control feed. In general, the study concluded that oral administration of *Vibrio* vaccine via feed improves immunity and increases production in shrimp farming ponds (Ray *et al.*, 2017).

In a study by Madsari *et al.* (2022), the efficacy of using a serine protease gene as a DNA vaccine was investigated to protect against *Vibrio parahaemolyticus* infection in *Litopenaeus vannamei*. The serine protease gene was mutated to replace the conserved residues Asp131, His82, and Ser231 with Asp, Gly, and Pro, respectively. Then, a pcDNA3.1 vector was constructed for the expression of mutVpSP (mutated serine protease) to study the DNA vaccine *in vitro* and *in vivo*. Transcriptional analysis of mutVpSP *in vivo* showed its expression in various tissues of vaccinated *Litopenaeus vannamei*, such as hemocytes, hepatopancreas, stomach, intestine, gills, and muscles. The efficacy of preventing *V. parahaemolyticus* infection in vaccinated shrimp was investigated, and the lowest cumulative mortality percentage was 30%, while the control shrimp had a cumulative mortality rate of 60%. The immune system was stimulated in shrimp vaccinated with DNA vaccine. The expression of mRNA of phenoloxidase, peroxinectin, and shrimp C-type lectin genes, which are the responding immune systems of shrimp, was significantly upregulated. Furthermore, humoral and cellular immune responses, including PO activity, phagocytosis, and encapsulation and nodule formation, increased. These results suggest that serine protease can be a virulence determinant of *V. parahaemolyticus*, and this DNA vaccine can be used as an effective vaccine for controlling acute hepatopancreatic necrosis (AHPND) disease syndrome in shrimp.

Methods of vaccine administration to shrimp

The main methods of administering vaccines to shrimp include oral administration through feeding, injection into the cephalothorax muscle, and administration via immersion. However, the rate of antigen uptake may differ among different organisms (Kulkarni and KV, 2022). Furthermore, the antigen must pass through the gut, which leads to a loss of immunogenicity. However, shrimp should be vaccinated in early life stages such as the post-larval or larval stage. Considering the size of the organism, oral and immersion administration are of the greatest importance. Furthermore, adding carboxymethyl 1,3- β-glucan (CMBG) to vaccination increases its efficiency (Sahul Hameed and Vimal, 2025). Wongtavatchai *et al.* (2010) reported that post-larvae of black tiger shrimp (*P. monodon*) and *Litopenaeus vannamei* were fed with *Vibrio* vaccine only, Vibromax, enriched with *Artemia*, and identified by the company Aqua Vac Vibromax (Schering Plough Animal Health) for 10 consecutive days and were then challenged with an immersion bath with *V. parahaemolyticus*. The general findings of this study showed that Vibromax™ increases the growth and survival of post-larvae. However, the efficacy of the vaccine may vary depending on the administered dose and the conditions that already existed for the post-larvae.

Enhancement of vaccine effectiveness using functional feed additives

Studies have shown that administering *Vibrio* vaccine with prebiotics increases the effect of vaccination on shrimp immune response (Khanjani *et al.*, 2022). β-glucan and Chitosan are common prebiotics used in aquaculture and has long been used as a dietary additive in aquatic animals to improve immune response (Sheikh Asadi *et al.*, 2024). β-glucan was involved in strengthening innate immune response in shrimp (Pooljun *et al.*, 2025). Oral administration of *Vibrio* vaccine with β-glucan led to an increase in bactericidal activity, phenoloxidase, and phagocytosis and ultimately led to better survival (Uengwetwanit *et al.*, 2025). Another potential prebiotic in this field is fucoidan, which is a polysaccharide derived from microalgae. It has been shown that administration of fucoidan through the diet increases shrimp immune response and consequently results in better survival in challenge with the pathogen compared to administering *Vibrio* vaccine alone. Therefore, in the construction of *Vibrio* vaccine, co-administration with prebiotics should be seriously considered to maximize the shrimp immune system response against a pathogen. Corrales Barrios *et al.* (2023) used fructooligosaccharides (FOS) as prebiotic at a concentration of 0.4%. Their results showed that the activity of proteases, phenoloxidase, and lysozymes was increased. As well as *Vibrio* spp. and *Pseudomonas* spp load were decreased. Regarding probiotics, its use alone improves the shrimp immune system (Tayyab *et al.*, 2025; De Stefano *et al.*, 2025).

Shrimp vaccination development studies: recent advances

The results of our review showed that the research trends from the late 1980s to the present reveals a fundamental shift from traditional pathogen inactivation methods toward advanced molecular and nanotechnologies (Elbahnaswy *et al.*, 2025; Hsu *et al.*, 2025). While classical studies (Table 1) primarily focused on formalin-killed cells and simple supplements, recent research has prioritized overcoming key limitations such as short-term immunity and low antigen stability within the digestive tract (Vandeputte *et al.*, 2024; Hsu *et al.*, 2025).

Table 1: Research conducted in relation to vaccination against *V. parahaemolyticus* in shrimp.

Pathogen	Species	Vaccine Type	Administration method	Efficacy	References
V. parahaemolyticus	*P. monodon*, *P. vannamei*	Formalin-killed *Vibrio* cells	Oral	Growth stimulant, survival of shrimp post-larvae	Wongtavatchai *et al.*, 2010
V. parahaemolyticus	*P. vannamei*	Formalin-killed *Vibrio* cells	Oral	increase in survival rate, promotion of shrimp health	Heidarieh *et al.*, 2010
V. parahaemolyticus	*P. vannamei*	Formalin-killed *Vibrio* cells	Oral and intramuscular	Selective enhancement of shrimp cellular defenses	(Powell *et al.*, 2011)

Madsari *et al.* (2022) introduced the first DNA vaccines against shrimp bacterial pathogens, demonstrating that targeted silencing of virulence genes, such as serine protease, could improve survival rates by approximately 30% compared with control groups. Parallel to these laboratory advancements, the transition of these technologies to industrial scales has accelerated, and extensive field trials have confirmed the efficacy of oral vaccination in commercial shrimp farms (Abidin *et al.*, 2026). Finally, the emergence of novel concepts such as trained immunity and the use of chitosan nanoparticles and bacterial vectors for vaccine delivery (Tables 2 and 3) has opened new horizons for the sustainable management of AHPND and WSSV, with the potential to induce more specific and durable immune protection in invertebrates (Jonjaroen *et al.*, 2025; Hsu *et al.*, 2025).

Table 2: Key studies and vaccination successes in recent years.

Pathogen	Shrimp Species	Vaccine Type	Administration Method	Achievement	Reference
V. parahaemolyticus	*L. vannamei*	DNA Vaccine (mutated *mutVpSP* gene)	Intramuscular Injection	Reduced mortality to 30%, stimulated immune genes	Madsari *et al.*, 2022
Vibrio spp.	*P. monodon*	Inactivated Bacterin	Oral	Improved survival, reduced anatomical deformities	Ray *et al.*, 2017
Major shrimp pathogens	*L. vannamei*	Bacterial vectors (Listeria)	Oral	Development of oral delivery systems using attenuated bacteria for antigen transfer.	Hsu *et al.*, 2025
Vibrio / WSSV	Various species	dsRNA-based vaccines	Nanoparticles	Utilization of RNAi for pathogen gene silencing and inducing specific protection.	Cheng *et al.*, 2025

Table 3: Emerging technologies in vaccine delivery and enhancement.

Emerging technology/material	Role in vaccination	Affected parameter	Mechanism of action	Reference
Chitosan Nanoparticles	Encapsulation of RNA vaccines	Antigen Stability	Protection against shrimp digestive enzymes.	Jonjaroen *et al.*, 2024
Trained Immunity	Strengthening immune memory	Adaptive-like responses	Priming the innate immune system	Hsu *et al.*, 2025
CRISPR/Cas9 Technology	Control of viral diseases	Genome Editing	Prevent viral replication.	Pudgerd e*t al.*, 2024

Conclusion

Shrimp farming is one of the important and growing sectors of the aquaculture industry. However, this section is still heavily influenced by the outbreak of viral and bacterial diseases. Although shrimp lack a classical adaptive immune system similar to vertebrates, studies have shown the existence of a type of trainable innate immunity. Accordingly, some commercial shrimp farms have used non-classical vaccination and immunization strategies in recent years to reduce disease incidence and increase specific pathogen resistance (SPR) shrimp against common pathogens (Hsu *et al*., 2025). The results obtained regarding immunological memory in shrimp indicate that shrimp vaccination can be a promising option in the shrimp aquaculture industry to control or manage disease occurrences such as AHPND. Therefore, it is essential that research efforts using materials derived from pathogenic *Vibrio* bacteria or inactivated whole *Vibrio* cells to stimulate the shrimp immune system against vibriosis be highlighted, focusing on the two commercial *Penaeid* species, *P. vannamei* and *P. monodon*. Although the results are not always the same, vaccinating shrimp with pathogenic subunits and DNA plasmids carrying antigen genes causes protective immunity against several pathogenic diseases. Shrimp vaccination is an acceptable choice for controlling or reducing the incidence of acute hepatopancreatic necrosis disease of shrimp. Shrimp vaccination easily strengthens its immune system for protection against a pathogen, consequently reducing disease incidence. However, in vaccine development and administration, actions such as optimal farm management based on health principles must be considered.

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