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Antibiotic alternative treatment methods in shrimp aquaculture

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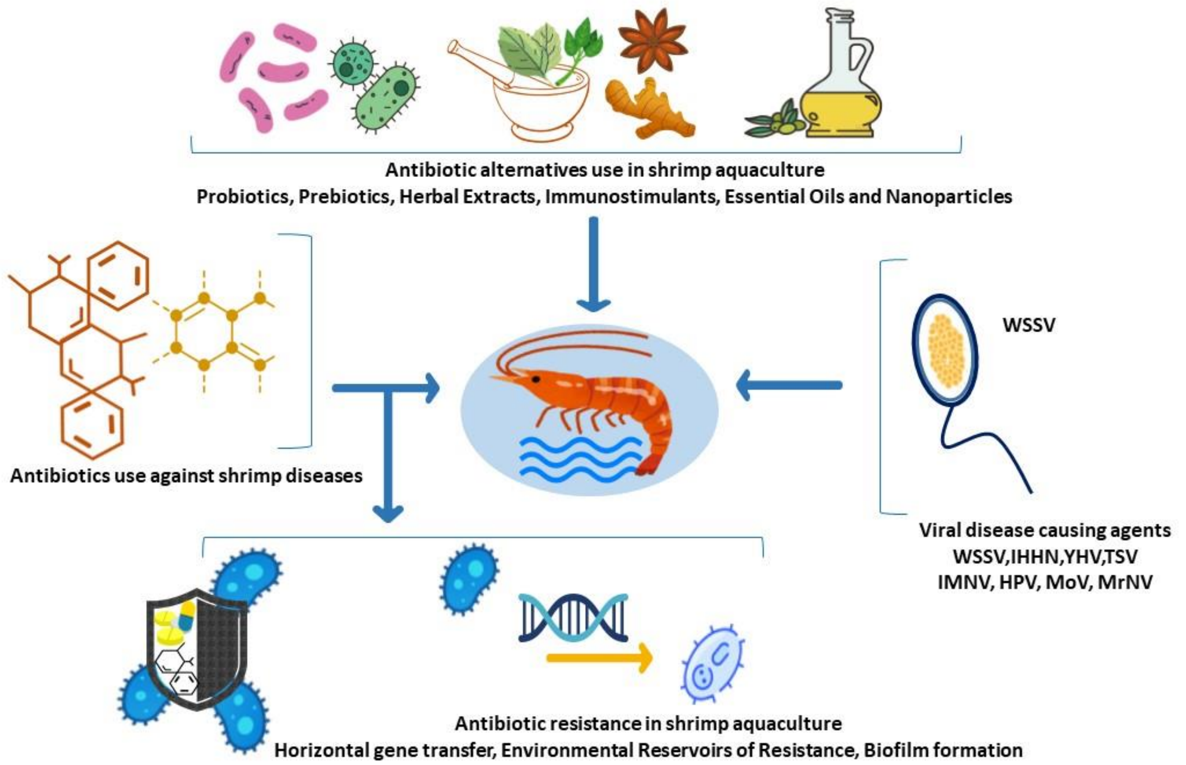
Abstract

Shrimp aquaculture is a key element of the global seafood sector. However, outbreaks related to bacterial and viral infections pose a serious threat to its productivity and sustainability. While the application of antibiotics has been a long-standing practice of combating these infections, their uncontrolled use has led to antimicrobial resistance, ecological disturbance, and perturbation of the beneficial microbiota. This review critically examines current antibiotic alternatives in shrimp aquaculture, with a particular focus on strategies targeting viral diseases. Emphasis is placed on biological approaches – using probiotics, prebiotics, immunostimulants, phytobiotics (e.g., herbal extracts & essential oils), and dietary interventions – as well as emerging technologies including nanotechnology and phage therapy. By synthesizing recent research, the review highlights eco-friendly, effective methods for enhancing shrimp health and disease resistance. It aims to bridge existing gaps in shrimp immunoprophylaxis and offer a framework for sustainable, antibiotic-free disease management in aquaculture.

Key words: shrimp health, antibiotic alternatives, probiotics, prebiotics, immunostimulants, nanotechnology, sustainability

Graphical Abstract



Highlights:

- Disease outbreaks pose significant challenges in shrimp aquaculture.
- Antibiotics are crucial but raise concerns such as resistance and environmental impact.
- Alternative strategies like probiotics, prebiotics, immunostimulants, herbal remedies, phage therapy, and nanoparticles offer promising solutions.
- Essential oils and nanoparticles show potential as natural antimicrobial agents.
- Collaboration between academia, industry, and regulatory bodies is essential for sustainable antibiotic alternatives in shrimp farming.

Aquaculture has become the main solution to address the increasing demand for fish products, as wild catches decline and aquaculture production exceeds capture fisheries. In 2022, global aquaculture produced about 18.32 million tons valued at US$250 billion (FAO, 2024). The industry operates in over 190 countries, cultivating more than 300 marine species (Anirudhan et al. 2021). During the blue revolution, shrimp emerged as one of the most successful species, remaining the most sought-after aquaculture species worldwide for years. Production surged from 75,000 metric tons in 1980 to 6.8 million metric tons in 2022 (Asmiya et al., 2025; Catalán et al., 2025; FAO, 2024). Vibriosis, caused by multiple Vibrio species, including *V. alginolyticus, V. anguillarum, V. campbellii, V. parahaemolyticus, V. harveyi, V. splendidus*, and *V. vulnificus*, poses a major threat to shrimp farming and various shrimp species (Mohamed et al. 2025; Tikadar et al. 2025). Bacterial infections caused by *Aeromonas hydrophila* (Maiti et al. 2025), *Pseudomonas* spp. (Gracia et al. 2024), and *Vibrio* species such as *V. harveyi, V. splendidus, V. alginolyticus, and V. parahaemolyticus* (Laynez-Roldán et al. 2024; Galindo-González, 2024; Mandal and Singh, 2024; Rodrigues et al. 2025) have led to significant economic losses. Some bacterial strains produce two toxins, PirA and PirB, which specifically harm the hepatopancreas (Sahoo et al. 2024). Saravanan et al. (2025) reported that around 60% of shrimp farming losses were due to the pale spot syndrome virus, with 20% caused mainly by Vibrio bacteria. Shrimp vibriosis remains a persistent concern for the global shrimp industry (Soto-Rodriguez et al. 2010). The widespread use of antibiotics has resulted in environmental contamination and health risks (Bilal et al. 2020; Muteeb et al. 2023; Sikder et al. 2024). Overuse and misuse of antibiotics lead to resistant microorganisms, complicating disease treatment. The emergence of antimicrobial resistance and genes has attracted global attention (Bhat et al. 2020; Salam et al. 2023; Sharma et al. 2024), prompting increased interest in developing new disease control methods and improving shrimp health. It is crucial to explore non-conventional strategies to reduce antibiotic use and enhance shrimp health and productivity (Emerenciano et al. 2022; Bondad-Reantaso et al. 2023). Alternative control methods include herbal remedies, bioremediation, and managing water quality factors like salinity, pH, dissolved oxygen, and nutrients to prevent disease outbreaks. Additionally, probiotics, prebiotics, synbiotics, and parabiotics, along with innovations in vaccine development and immune stimulation, should be actively implemented within comprehensive health programs to combat bacterial, viral, and stress-related diseases (Citarasu et al. 2022; Vijayaram et al. 2024). Specific infectious agents requiring mandatory reporting (Thornber et al. 2020; Ilkhas et al. 2024;Covarrubias et al. 2025;) can be managed effectively through these preventive and control measures, although shrimp management remains challenging. Notably, some bacterial strains have developed resistance to certain antibiotics, such as *V. harveyi* to oxytetracycline and *Aeromonas hydrophila* to ampicillin (Hossain et al. 2021; Aly and Fathi 2024; Abraham et al. 2025), which has limited the success of disease prevention efforts. Nonetheless, these strategies can help reduce microbial diseases in shrimp cultivation. However, many shrimp producers and technicians still believe antibiotics are essential for treatment and prophylaxis to prevent bacterial outbreaks (Sazali et al. 2024).

Beneficial microbes like lactic acid bacteria and bacilli, are commonly used as probiotics and have a variety of benefits, such as improved gut health, competitive exclusion of pathogenic microorganisms, and an improved immune response. Information is available that probiotics can reduce both the incidence of bacterial and viral infections in shrimp, thus reducing the use of antibiotics (Calcagnile et al. 2024; Vijayaram and Kannan 2018; Vijayaram et al. 2024). Recently, antimicrobial peptides (AMPs) have gained immense academic attention due, for instance, to their new antibacterial mechanisms (Aweya et al. 2021; Naiel et al. 2023; Shan et al. 2024). AMPs are characterised by their cationic and amphiphilic characteristics, which render them as short peptides with the ability to bind to or insert into bacterial cells, attributed to their biochemical properties and small size (Xia et al. 2021; Akhavan-Bahabadi et al. 2024; Rodrigues et al. 2025).

Prebiotics are indigestible polysaccharides incorporated in diets to influence the host beneficially (Li et al. 2021; Wang et al. 2024). They selectively stimulate the growth and enhance colonisation of specific gut-friendly microbes residing in the digestive system. Prebiotics in the diet help strengthen the immune system, modulate gut microbial balance, and improve general health, thereby enhancing disease resistance (Chunchai et al. 2018; Qamar et al. 2018). Naturally derived immunostimulants, including the blue-green algae *Spirulina platensis* (Ringø 2025), polysaccharides extracted from seaweeds like carrageenan, sodium alginate, and fucoidan, as well as red seaweed-derived extracts, alongside polysaccharides sourced from the fungi *Nodulisporium* sp. KT29 and *Trichoderma* sp., demonstrate efficacy in enhancing the innate immune system of Pacific white shrimp (*Penaeus vannamei*). Administration of these immunostimulants leads to significant improvements in non-specific immune markers, including total haemocyte count, phagocytic activity, phenoloxidase function, respiratory burst, superoxide dismutase levels, and plasma protein content (Akbar Ali et al. 2022; Devi et al. 2023). Apart from traditional approaches, naturally occurring immunostimulants have also been discovered with great success to induce disease resistance in Pacific white shrimp, especially against pathogens such as infectious myonecrosis virus (IMNV), white spot syndrome virus (WSSV), and *V. harveyi*. Such compounds have been associated with remarkable improvement in survival rates in shrimp (Muahiddah et al. 2022). Among them, marine-derived compounds such as β-glucans, nucleotides, and polysaccharides have been reported to trigger significant features of the native immune response. These include triggering of the prophenoloxidase cascade, stimulation of phagocytic activity, and upregulation of immune-related gene expression. Their action mode renders them appropriate to be used as alternatives to antibiotics in aquaculture management of bacterial and viral diseases (Kumar et al. 2023; Novriadi et al. 2024; Madhulika Meinam et al. 2025).

Immunostimulants have been known to improve disease resistance by triggering the production of antimicrobial peptides, enhancing phagocytosis, and immune effector cells (Hien et al. 2019; Pothiraj et al. 2023; Subbarayudu et al. 2024; Uengwetwanit et al. 2025). Apart from these, compounds with multifunctional bioactivity, such as antimicrobial, antioxidant, immunomodulatory, growth-promoting, and anti-inflammatory activities, have become trendy to ensure general well-being and robustness in aquatic animals. Despite their advantages, the use of such bioactive compounds in aquafeeds is associated with some constraints, mainly due to the requirement of standardized and reproducible protocols to ensure uniform quality of feed and optimal physiological action in the farmed animals (Firmino et al. 2021; Ragunath and Ramasubramanian, 2022). Immunostimulants enhance the immune responses in aquatic animals and their resistance to pathogenic microorganisms (Nolasco-Alzaga et al.2025).

Bioactive immunostimulants have been reported to be useful in the control of pathogens of aquatic species, like shrimp and fish, which are vulnerable to a broad range of pathogens (*Aeromonas hydrophila*, *Aeromonas salmonicida*, *Vibrio anguillarum*, *Vibrio vulnificus*, *Vibriosalmonicida*, *Streptococcus* spp., *Yersinia ruckeri*), viruses (causing yellow head disease, viral haemorrhagic septicaemia, and hematopoietic necrosis), and parasites such as *Ichthyophthirius multifiliis*. The use of the above immunostimulants has a significant role in the improvement of survival rates and reduction of mortality rates of whiteleg shrimp (*Litopenaeus vannamei*)(Sadat Hoseini Madani et al. 2018). In addition, plant-derived immunomodulators are increasingly of interest to boost the immune response of shrimp against White Spot Syndrome Virus (WSSV). These naturally occurring compounds, extracted from a range of marine flora and herbs, offer a promising alternative or supplement to traditional chemical treatments, potentially reducing dependence on antibiotics and improving the sustainability of shrimp farming processes (Ghosh et al. 2021).

Medicinal plants, or phytobiotics, and their extracts and essential oils are crucial for appetite stimulation, growth promotion, and immunostimulation of aquatic animals (Sumana et al. 2025). Essential oils (EOs) are very popular because of their activity as natural antioxidants and immunostimulation agents (Grazul et al. 2023; Ballester et al. 2025). Chemical composition of EOs is gastric acid-resistant, retaining effectiveness and effect (Aydın and Barbas 2020). Aromatic EOs from plants possess wide antimicrobial activity through the inhibition of microbial cell membranes, enzymes, and metabolic processes. The use of EOs in shrimp feed or pond water has been reported to have potential in bacterial disease effects and enhancement in shrimp health (Soowannayan et al. 2019; Dias et al. 2018). Aromatic oils primarily modulate the gut microbiota by suppressing pathogenic bacterial strains, thereby creating a favorable environment for the proliferation of beneficial microbial populations. (Sokol et al. 2025). The indirect action of EOs on intestinal microbiota can be attributed to alterations in gut conditions, changes in pH levels as well as changes in the nature and amount of intestinal mucosa secretions (Mo et al. 2022; Liñán-Atero et al. 2024). Experimental studies have shown that dwarf lilyturf (*Ophiopogon japonicus*) (Chen et al. 2021), geniposidic acid (Huang et al. 2020), coumarin (Shan et al. 2021), as well as a variety of other phytotherapeutic agents, show excellent efficacy against the prevention and treatment of WSSV. Effective monomer compounds revealed in herbal remedies are highly purified substances with well-defined chemical compositions, and their modes of action are to be elucidated.

Bacteriophages (phages) are promising as effective biocontrol agents for the management of microbial infections in shrimp culture, due to their high lytic activity and several advantages over traditional antibiotic treatments (Aziz et al. 2024; Yang et al. 2025). As self-replicating, naturally occurring viruses of bacterial pathogens, bacteriophages are an environmentally friendly and relatively inexpensive alternative to traditional antimicrobials (Wani et al. 2024; Ashraf et al. 2025). Lytic activity of such phages as vB_VpS_BA3 and vB_VpS_CA8, extracted from sewages, has been proved to show lytic activity against multidrug-resistant *Vibrio parahaemolyticus*, a significant pathogen causing vibriosis in shrimp, are shown in previous research (e.g., Yang et al. 2020; Liang et al. 2022; Chen et al. 2023). Bacteriophages, due to their high specificity and high lytic efficiency, act as highly effective biological control agents against bacterial pathogens in aquaculture farming. Their natural occurrence in water bodies and specificity in infecting target pathogens without injuring beneficial microbial populations render them more desirable. Phages are easily administered in feed or water and are also environmentally friendly, with no reported toxicities in aquatic host or habitats (Golkar et al. 2014; Kushwaha et al. 2024; Xu et al. 2025). When the world is threatened with antibiotic resistance, phage therapy is a targeted measure free of the broad ecological effects of traditional antimicrobials, including microbiome disruption and drug-resistant development of microbes. In aquaculture, members of genus *Vibrio* are the main target organisms of phage utilisation. Positive outcomes have been recorded in several pathogenic species, such as V. *harveyi, V. alginolyticus, V. vulnificus, and, more prominently, V. parahaemolyticus*, including AHPND-producing strains (Vandeputte et al. 2024). The move of aquaculture into inland waters subject to brackish effects has been the impetus behind phage therapy due to rising bacterial pressures and widespread misuse of antibiotics. The use of multiphage preparations, known as phage cocktails, is gaining preference to increase efficacy and limit the emergence of resistance. Such products employ overlap host-range lytic phages to achieve maximum therapeutic coverage and stability. Advances in high-resolution imagery and genomic evaluation have immensely improved knowledge on phage biology, morphology, and safety profiles critical to the regulatory approval and therapeutic efficacy (Ramos-Vivas et al. 2021; González-Gómez et al. 2023). Metal nanoparticles, such as preparations comprising silver, copper, zinc, and selenium, have high antimicrobial efficacy with a broad spectrum of efficacy against all manner of pathogens, including bacteria, viruses, and fungi. The addition of these nanoparticles to shrimp feeds or their use in water treatments will prevent the growth of pathogenic microorganisms. This measure does more than upgrade shrimp health but also reduces the dependency on conventional antibiotics applied in agriculture (Ahmed et al. 2024; Vijayaram et al. 2024).

The present study proposes to underscore the potential of these biologicals and nanomaterials as promising alternatives to antibiotics, showcasing an emerging tool in the management of shrimp aquaculture diseases.

Viral infections in shrimp aquaculture

Viral diseases continue to be major obstacles to shrimp aquaculture, both to the health of farm animals and to the sustainability of farming operations over the long-term horizon (Asche et al. 2021; Tien Nguyen et al. 2024). Several viral pathogens have been identified as significant causes of disease outbreaks among cultured shrimp populations. These pathogens include Penaeus Stylirostris Densovirus (PstDV), Hepatopancreatic Parvovirus (HPV), Taura Syndrome Virus (TSV), Infectious Hypodermal and Hematopoietic Necrosis Virus (IHHNV), White Spot Syndrome Virus(WSSV), and Yellow Head Virus (YHV) (Magbanua et al. 2000; Tang and Lightner 2006; Pinheiro et al. 2007; Lightner 2011; Singh, 2025; Lee et al. 2022). Notable is the fact that WSSV has been reported to be one of the most virulent pathogens, presenting generally as white spots on the carapace, lethargy, and high, rapid mortalities among the infected shrimp populations (Lightner 1999; Soowannayan and Dong 2022; Bhassu et al. 2024). Similarly, YHV is the etiologic agent of YHD, characterized by a yellowing of the cephalothorax, extensive tissue necrosis, and elevated mortality, targeting specifically juvenile black tiger shrimp (*Penaeus monodon*) (Singh, 2025). TSV causes sudden die-offs, especially of postlarval and juvenile shrimp, which tend to pose considerable economic losses to producers (Cabanillas-Ramos et al. 2024). Meanwhile, IHHNV infects the hepatopancreas largely, causing extensive tissue damage and loss of function, which impacts shrimp growth and survival in general (Tang and Lightner 2017). HPV targets hepatopancreatic epithelial cells, producing gross lesions and reduced growth performance in affected shrimp (Orosco et al. 2017). To manage viral diseases, various strategies such as biosecurity measures, including broodstock screening and facility disinfection, are used to prevent pathogen introduction and spread (Shrivastava, 2024; Chrisolite et al., 2025). Vaccination and selective breeding for disease resistance are also being investigated as potential interventions. Ongoing research aims to deepen our understanding of shrimp viral diseases, leading to the development of effective diagnostics, vaccines, and therapies to control these pathogens in aquaculture settings (Table 1).

Table 1. Common pathological viruses and their sensitivity

Virus	Symptoms	Sensitivity	Reference
WSSV	White spots or patches on the exoskeleton of shrimp. Loss of appetite, lethargy and reduced activity	Susceptible to antiviral agents such as interferon and RNAi-based therapies.	Alfaro et al. (2021)
IHHNV	Necrotic lesions on the cuticle of shrimp. hematopoietic tissue necrosis	Resistant to antiviral treatments, limited control options available.	Leyva-Madrigal et al. (2011)
TSV	Necrotic lesions on the cuticle of shrimp. Necrosis of the lymphoid organ (lymphoid organ atrophy)	Sensitive to RNAi-based therapies, vaccination shows promise for prevention.	Cruz-Flores et al. (2021)
YHV	Yellow discoloration of the cephalothorax (head and thorax).	Limited antiviral options and biosecurity measures are	Havanapan et al. (2021)

	anorexia and reduced feeding	crucial for prevention.	
IMNV	Rapid mortality in shrimp. Melanized spots on the exoskeleton of shrimp (spotting)	Susceptible to RNAi-based therapies, limited antiviral options are available.	Andrade et al. (2008)
HPV	Reduced appetite, slow or stunted growth, abdominal swelling or distension, pale or opaque hepatopancreas, increased mortality rates	Varied, typically higher in younger shrimp. More susceptible during periods of stress. Increased sensitivity in post-larval stages	Singaravel et al. (2021)
MoV	Loss of appetite, excessive molting, body discoloration, reduced growth rates, Increased mortality rates	Varied, may affect all age groups. More common in juvenile and subadult stages. Higher susceptibility in stressed populations	Cowley (2020)
Macrobrachium rosenbergii nodavirus (MrNV)	Erratic swimming behaviour, loss of appetite, body discoloration, empty gut or digestive tract, reduced growth rates	Varied, may affect shrimp of all ages, Higher susceptibility in stressed populations, more common in juvenile and subadult stages.	Ravi et al. (2009)
Extra small virus (XSV)	Reduced feeding activity, slow or stunted	Varied, may affect shrimp of all ages, Higher	Chen et al. (2021)

	growth, abnormal swimming behaviour, increased mortality rates	susceptibility in stressed populations, More common in juvenile and subadult stages

White Spot Syndrome Virus (WSSV)

White Spot Disease (WSD), a viral infection caused by the *White Spot Syndrome Virus* (WSSV), is one of the most significant viral risks to the global shrimp aquaculture industry. The disease is spreading quickly across major shrimp-producing areas, including Southeast Asia, South Asia, Latin America, and East Asia (Hauton et al. 2015; Peruzza et al. 2020). WSSV is highly virulent, especially in penaeid shrimp; however, its host range is much broader than shrimp and includes many aquatic arthropods such as crabs, copepods, caridean shrimp, and crayfish. The virus's ability to infect so many species highlights its ecological significance and the significant health problems it causes to cultured and feral aquatic populations. Among penaeid shrimp, WSSV is reported to infect *Penaeus* species such as giant tiger prawn, Indian white shrimp (*P. indicus*), kuruma shrimp (*P. japonicus*), Chinese white shrimp (*P. chinensis*), red tail shrimp (*P. penicillatus*), green tiger shrimp (*P. semisulcatus*), brown shrimp (*P. aztecus*), Pacific white shrimp, banana shrimp (*P. merguiensis*), and blue shrimp (*P. stylirostris*), along with hardback shrimp (*Trachypenaeus curvirostris*) and greasyback shrimp (*Metapenaeus ensis*). WSSV infects not only penaeid shrimp but also other caridean shrimp such as *Exopalaemon orientalis* and the economically valuable giant river prawn (*Macrobrachium rosenbergii*). Red swamp crayfish (*Procambarus clarkii*) are also infected (Saravanan et al. 2025). The disease will normally create high mortality rates rapidly, within three to ten days post-infection (Peruzza et al. 2020). WSSV is highly virulent and continues to be a significant issue for shrimp aquaculture globally. The virus, in extreme epizootics, has the potential for rapid and nearly complete breakdown of populations, with mortality rates of up to 100% in infected shrimp within a few days, causing huge economic losses, particularly in Pacific white shrimp culture (Saravanan et al. 2025).

Taura Syndrome Virus (TSV)

TSV was first identified in 1992 from Pacific white shrimp in Ecuador's Taura River, hence the name "TSV disease" (Stentiford et al. 2009), with its viral etiology confirmed in 1995. Since then, it has been reported in the Americas (e.g., Colombia, Honduras, USA, Mexico), Asia (e.g., Thailand, Indonesia, China, Myanmar), Africa, and the Middle East (e.g., Saudi Arabia), reflecting its global spread. TSV infection progresses through three phases in white-leg shrimp: the acute stage (within seven days post-infection, following a two–five-day asymptomatic period), the transition stage (about five days), and the chronic stage (in survivors post-molt), with mortality rates between 60% and 90% (Poulos et al. 2006). TSV is an icosahedral, non-enveloped virus possessing a ~10.2 kb positive-sense single-stranded RNA genome and a particle size of roughly 32 nm (Fadilah et al. 2021). It primarily affects the hepatopancreas, disrupting shrimp metabolism and contributing to economic losses. The virus also invades the antennal glands, subcuticular connective tissues, lymphoid organs, and striated muscles. Damage to these tissues impairs vital physiological functions; infection of striated muscles causes muscle necrosis, leading to reduced mobility and physical deterioration (Brock et al. 1997; Lightner, 2011). New strains of TSV continue to re-emerge due to its ability to adapt to a wide range of penaeid shrimp species and environmental conditions (Cruz-Flores et al. 2021). These symptoms result from viral targeting of the shrimp's cuticular epithelium and connective tissues, leading to necrosis and lesions evident during moulting. Affected shrimp often show soft shells and increased susceptibility to secondary infections due to compromised exoskeletal integrity (Covarrubias et al. 2025). TSV is a significant viral pathogen that causes severe disease in farmed shrimp culture and inflicts acute mortality and widespread economic damage on the global shrimp farming industry. Acute TSV infection in white leg farmed shrimp is marked by reddening of the body, especially on the tail, uropod's, and appendages, as a result of the hypertrophy of the chromatophores. The other symptoms are abnormal black melanised spots underneath the cuticle, loss of appetite, abnormal swimming, lethargy, soft cuticles, flaccid bodies, and opaque musculature (Dhar et al. 2004).

Early Mortality Syndrome (EMS) or Acute Hepatopancreatic Necrosis Disease (AHPND)

AHPND is a highly acute infection that targets shrimp. Several *Vibrio* bacteria cause it and have significantly affected shrimp farming worldwide in recent years because it attacks rapidly, has a multifactorial ethology, and targets multiple sites (Cruz-Flores et al. 2019; Powers et al. 2021). Acute Hepatopancreatic Necrosis Disease (AHPND) was initially detected in China in 2009 and has since emerged in several other regions, notably across Southeast Asia, including Vietnam, Malaysia, Thailand, the Philippines, and Bangladesh, as well as parts of South America (Mexico, USA). In 2017, the World Organisation for Animal Health (WOAH) officially declared it as a disease (Cruz-Flores et al. 2019; Restrepo et al. 2018). Acute Hepatopancreatic Necrosis Disease (AHPND) is most associated with *Vibrio parahaemolyticus* strains, referred to as VP-AHPND, that produce a potent toxin targeting the hepatopancreas, a vital digestive organ in shrimp. This toxin causes the epithelial cells of the organ to slough off, leading to rapid deterioration of shrimp health (Thitamadee et al. 2016). AHPND, also known as Early Mortality Syndrome (EMS), is linked to *V. parahaemolyticus* strains carrying the pirAB toxin genes, which are responsible for the onset of acute clinical symptoms, including sudden mortality, a pale and atrophied hepatopancreas, and an empty digestive tract (Tran et al. 2013; Soto-Rodriguez et al. 2024). The disease progresses swiftly, often resulting in widespread shrimp deaths within days of infection and causing significant financial losses, particularly in regions heavily dependent on shrimp aquaculture. Outbreaks of EMS/AHPND have severely impacted shrimp farming industries in Southeast Asia and Latin America, where large-scale operations are common and economically critical (Luu et al. 2021). Clinical signs of AHPND are well documented: infected shrimp typically display a shrunken, discoloured hepatopancreas, often pale due to the loss of pigment cells, and in some cases, dark spots caused by melanisation. These symptoms reflect extensive tissue damage and underscore the devastating nature of this disease in affected populations. Other manifestations include soft shells, resulting from compromised calcium absorption, and flaccid exoskeletons. The middle part of the gut in infected shrimp is usually empty, indicating that they do not consume food and cannot digest it (Powers et al. 2021). Sick shrimp typically have a small, pale, or white hepatopancreas; are lethargic; exhibit slow growth; have soft shells; and have a milky-looking stomach (Lai et al. 2015).

Yellowhead Virus (YHV)

YHD has been documented in black tiger shrimp in Asian regions such as Vietnam, the Philippines, Sri Lanka, Indonesia, Malaysia, India, and China, but laboratory confirmation has been rare (Wijegoonawardane et al. 2008). *Yellowhead virus* (VHV) is highly infectious and results in yellowing of the cephalothorax, lethargy, and extremely high shrimp mortality. Fatigue is also evident in infected shrimp, along with reduced appetite and erratic swimming (Arulmoorthy et al. 2020; Villanueva-Segura et al. 2020). Due to the simplicity of the disease transmission, early detection and control are extremely important to avoid drastic losses in shrimp culture (Wongteerasupaya et al. 1997; Akhila et al. 2025; Sridulyakul et al. 2011). Yellow head virus (YHV) epizootics have caused serious economic issues in shrimp aquaculture. YHV genotype 1 (YHV-1) and the associated gill-associated virus (GAV or YHV-2) were initially discovered in the 1990s as major viral pathogens of farmed black tiger shrimp in Thailand and Australia. Infected shrimp typically exhibit well-defined symptoms like yellow cephalothoracic colour, sluggishness, and high mortality that may progress within a few days of infection. The intensity of these viral epizootics has caused huge losses to shrimp farmers, which requires an urgent need for better disease control measures and enhanced safety measures (Cowley et al. 2019). YHV-1 is a capsid-budded, rod-shaped virus that contains a positive-sense, single-stranded RNA genome. The particles of YHV-1 are approximately 40–60 nm in width and 150–200 nm in length. The virus has helical nucleocapsids within the capsid, approximately 15 nm in width and 80 to 450 nm in length (Soowannayan et al. 2015; Walker and Sittidilokratna 2008). YHV particles consist of three primary proteins: two envelope glycoproteins (gp116 and gp64) and one internal nucleoprotein (p20). The gp116 glycoprotein is the primary protein that makes the virus virulent. It plays a very crucial role in the virus infecting and damaging the host cells (Havanapan et al. 2021). Specific disease symptoms, such as yellow pigmentation of the cephalothorax and gills, are characteristic of YHV genotype 1 infection. Yet, prolonged infection with YHV-1 is sometimes possible without overt clinical signs, like the outbreaks of WSSV (Anantasomboon et al. 2008).

Gill-associated Virus (GAV)

Gill-associated virus (GAV), or YHV-2, appeared around the same period as YHV-1 in Australia and is very closely related to other viruses. Both YHV-1 and YHV-2 are thought to be virulent pathogens, but GAV causes chronic infection with lower mortality compared to YHV-1. Still, it remains a severe risk to Australia's shrimp farms. Combined, the viruses have inflicted a severe blow to shrimp farming in Thailand and Australia, where the giant tiger shrimp is a major aquaculture species (Cowley et al. 2002; Walker and Mohan 2009). GAV, a Yellowhead virus (YHV-2) variant, infects mainly the gills of shrimp, causing gill discoloration and respiratory distress (Balasuriya et al. 2022; Hooper et al. 2023). Respiratory distress from infection by GAV normally progresses into lethargy and eventually causes higher mortality rates in shrimp populations (Nunan et al. 1998; Spann et al. 1997; Walker et al. 2001). Recent studies have increased our understanding of the ethology, pathogenesis, and clinical manifestations of GAV infection in shrimp culture (Kumar et al. 2021; Murugan et al. 2024). GAV is believed to have originated from marine ecosystems, likely from natural reservoirs or other aquatic infected hosts (Johnson et al. 2008). During infection, the virus infects gill tissues primarily, inducing replication that leads to cellular damage and inflammation, eventually impairing respiratory function (Lee et al. 2024). Infected shrimp can develop signs such as respiratory distress, lethargy, reduced swimming activity, and evident gill abnormalities, rendering the gills discoloured and showing necrotic lesions (Jeon et al. 2024). Furthermore, GAV infection often leads to reduced feeding activity and growth impairment, thereby affecting shrimp health and farm productivity in general (Arulmoorthy et al. 2020).

Contagious Hypodermal and Hematopoietic Deterioration Virus (IHHNV)

Infectious hypodermal and hematopoietic necrosis virus (IHHNV), a parvovirus, is among shrimp aquaculture's most important viral pathogens. The virus occurs in penaeid shrimp species and is associated with various clinical signs, such as the development of necrotic lesions on the cuticle, lethargy, stunted growth, and higher rates of mortality (Aly et al. 2021; Imsonpang et al. 2024). IHHNV poses serious hazards, particularly in blue shrimp (*Penaeus stylirostris*), where it causes deformities such as cuticular lesions in surviving shrimp. The virus targets epithelial cells for infection of the cuticle and hematopoietic tissues, causing widespread cellular necrosis and a decrease in haemocyte levels. This weakens the immunity of the shrimp and elevates mortality rates during outbreak phases (Manikavel et al. 2018; Waiho et al. 2024). Furthermore, the effects of IHHNV extend beyond health complications, with major interference with growth performance and farm productivity. Historically, one of the most catastrophic and earliest outbreaks occurred in 1981 when the virus was detected in post-larvae and juvenile blue shrimp imported from Costa Rica and Ecuador to a Hawaiian shrimp farm. This led to mortality rates reaching 90%, demonstrating the destructive capacity of IHHNV in aquaculture systems. It was subsequently detected during the quarantine procedures for imported whiteleg shrimp at a Taiwan shrimp farming farm in 1986 and subsequently in black tiger shrimp farming in Australia during 2008 (Rai et al. 2012). Its negative impacts are to reduce the commercial value of shrimp due to stunted growth, irregular development, and epidermal deformities at harvest. This is especially seen through the formation of RDS (rostrum deformities syndrome), which comprises irregularities in the cuticle of the rostrum, antennae, thoracic, and abdominal areas (Leyva-Madrigal et al. 2011). The IHHNV genome is made up of three open reading frames (ORFs), two coding for non-structural proteins (NS1, 2001 bp, and NS2, 1092 bp) and one coding for virus capsid proteins (CP, 990 bp) (Chai et al. 2016).

Monodon-type baculovirus (MBV)

Monodon-type baculovirus (MBV), known as singly enveloped nuclear polyhedrosis virus (PmSNPV), is one of the best-studied viral shrimp diseases (Alcivar-Warren et al. 1994). All the studies have revealed that black tiger shrimp are readily infected by MBV at various growth stages, particularly at the late larval, post-larval, and early juvenile stages. The virus infects epithelial cells of hepatopancreatic tubules and ducts, particularly in post-larvae, juveniles, and adults. In addition, MBV targets the anterior midgut epithelium in post-larval shrimp, contributing to compromised digestive and absorptive functions during these critical early stages of growth and development. Initially identified in Taiwan, MBV has since been documented in various regions around the world, affecting different penaeid shrimp species (Lightner and Sindermann, 1988; Lightner and Redman, 1992; Seethalakshmi et al. 2021). Classified as a double-stranded DNA virus, MBV exhibits a rod-shaped, enveloped structure and is traditionally categorised as a type A baculovirus. The dimensions of MBV particles typically range between 265 and 324 nm in length and 42 and 77 nm in width (Rajendran et al. 2012). While the genetic material of MBV is circular in structure, the exact genome size varies from 80 to 160 kbp, although the full genome sequence remains elusive. MBV has a broad host range, infecting both wild-caught and cultivated shrimp species, including freshwater prawns like the giant river prawn (Dong et al. 2021).

Laem-Singh virus (LSNV)

The occurrence of Monodon Slow Growth Syndrome (MSGS) in black tiger shrimp was first noted in Thailand in 2001, when farmers started noticing an unexplained slowdown in the growth of juvenile shrimp at about one month of age. Characterized by drastically diminished growth and compromised feed conversion, MSGS soon became a serious problem in the shrimp aquaculture industry. Initial investigations implicated a variety of potential causes, ranging from viral infections to nutritional deficiency and environmental stress. More recent evidence, however, indicates that the disease stems from a multifactorial interaction among pathogenic factors and aquaculture management procedures (Withyachumnarnkul, 2005). One of the most important pathogens suspected of being implicated in MSGS is *Monodon-type baculovirus* (MBV or MBassin), whose virulence is intimately linked to the expression of certain genes that enable viral replication and immune evasive strategies. In particular, MBV or MBassin contains the major capsid protein (MCP), a critical factor in virus assembly and dissemination within the host tissue (Méndez et al. 2004). Aside from structural proteins, MBV or MBassin contains genes for viral anti-apoptotic proteins and mimics of suppressor proteins that interfere with host immune signaling, e.g., interferon-like molecules. These viral proteins appropriate the shrimp innate immune defences by inhibiting apoptosis in haemocytes and dampening the host expression of immune effectors such as prophenoloxidase (proPO), antimicrobial peptides (AMPs), and components of the Toll and IMD pathways. This immunosuppression compromises the host's ability to defend itself effectively, making it more susceptible to secondary infection and delaying recovery from disease (Goertz and Hoch, 2008). Moreover, MBV or MBassin interference with cell cycle regulation and apoptotic mechanisms is likely to be involved in the stunted growth and developmental defects seen in infected shrimp (Santos et al. 2014).

Loose shell syndrome (LSS)

Loose Shell Syndrome (LSS) initially manifested in black tiger shrimp in the late 1990s in India, in aquaculture ponds around the Vellar estuary in Tamil Nadu. In 1998–1999 reports, about 23% and 14% of the shrimp farms, respectively, reported outbreaks of LSS, citing it as a newly emerging threat to commercial shrimp culture (Mayavu et al. 2003; Naik et al. 2020). LSS was reported in both the summer and winter crop cycles, suggesting that it can survive under different environmental conditions. A loosely attached or soft exoskeleton, decreased feed consumption, lethargy, and overall weakness in infected shrimp characterized the syndrome. Follow-up studies identified the causative agent as the *Loose Shell Syndrome Virus* (LSNV), a single-stranded RNA (ssRNA) virus. LSNV seems to interfere with the synthesis of structural proteins needed for exoskeletal development, thereby inhibiting the normal process of molting and compromising the shell structure (Huynh, 2023; Wang et al., 2024). Similar to many RNA viruses, the ssRNA genome of LSNV has a high rate of mutation, making it difficult to control the disease since the virus can adapt and evolve easily. Pathological effects of LSNV have significant effects on shrimp health and growth performance, lowering their market value and survival rate. Structurally, LSNV is a non-enveloped virus with an icosahedral structure, about 27 nanometers in diameter (Xu et al. 2023; Jonjaroen et al. 2024). Its physical properties closely resemble members of the Luteoviridae family, a family of plant-infecting ssRNA viruses, which indicates an evolutionary relationship. The compact icosahedral capsid of LSNV is optimised to safeguard its RNA genome, allowing efficient replication and persistence in aquaculture environments. Given its rapid spread and detrimental effects, LSS remains a significant concern for shrimp farmers, necessitating vigilant monitoring and improved management strategies.

Infectious Myonecrosis Virus (IMNV)

Infectious myonecrosis (IMN) is a viral disease caused by the infectious myonecrosis virus (IMNV) in penaeid shrimp. IMNV is a significant risk to global shrimp aquaculture, especially to whiteleg shrimp culture systems (Andrade et al. 2008; Borsa et al. 2011). The disease was first detected in cultured shrimp in the northeastern region of Brazil in 2003 and since then has been reported in several countries, including India (2016), Malaysia (2018), and Indonesia (2018) (Jithendran et al. 2021; Santhosh Kumar et al. 2021). Outbreaks of IMN tend to be concurrent with environmental stress conditions, i.e., sudden changes in the water temperature and salinity, along with the consumption of substandard feed (Lightner, 2011). PsIMNV is a member of the Totiviridae family, consisting of double-stranded RNA viruses primarily known to infect protozoans and fungi. Molecular and phylogenetic analysis confirms its position in this family, namely analysis of the RNA-dependent RNA polymerase (RdRp) gene (Borsa et al. 2011; Sahul Hameed et al. 2017). The virus attacks primarily the striated muscle tissue of the shrimp; however, secondary effects can extend up to the gills and lymphoid tissues. In the chronic stage of the infection, there is apparent muscle breakdown, with histological analysis indicating coagulative necrosis and liquefaction of the tissues (Prasad et al. 2017). Clinically, infected shrimp have reduced body translucency and can have necrotic lesions in the cephalothoracic and abdominal areas. Other important indicators are discoloration of the tail fan and a significantly attenuated hepatopancreas. As the disease progresses, necrotic damage can extend up to the tail musculature, leading to further tissue breakdown (Teixeira-Lopes et al. 2011). Infected shrimp typically have pale coloration or show reddish musculature, along with opaque or whitish lesions in the abdominal area, indicating the presence of traumatized striated muscle fibers (Poulos et al. 2006).

White Tail Disease (WTD)

White Tail Disease (WTD) is a critical threat in shrimp culture, particularly to the larval and early post-larval development stages. WTD is primarily associated with the co-infection of giant river prawn nodavirus (MrNV) and the extra small virus (XSV), which synergistically cause broad pathological impacts in shrimp populations (Hameed and Bonami, 2012). Infectious hypodermal and hematopoietic necrosis virus (IHHNV) was first reported in Guadeloupe, with initial observations dating back to 1995; however, formal documentation and confirmation of the outbreak were around 1997, which has led to some uncertainty regarding the precise year of its emergence. The disease gained prominence afterward and was later identified in Australia (2008), Martinique (1999), China (2003), India (2004), Malaysia (2012), Thailand (2006), and Taiwan (2006) (Chen et al. 2021; Ravi et al. 2009). Naturally occurring WTD infections have been observed in giant tiger prawn and Indian white shrimp breeding facilities, particularly near giant river prawn hatcheries with reported WTD infections, suggesting potential transmission routes of MrNV, as well as the transmission of XSV from giant river prawn to giant tiger prawn and Indian white shrimp (Ravi et al. 2009). MrNV primarily targets hemocytes and muscle nuclei in the lower abdomen of infected shrimp, subsequently spreading throughout the body via haemolymph circulation, often accompanied by XSV (Chen et al. 2021). Structurally, MrNV is a minute icosahedral virus that is non-enveloped and consists of two single-stranded RNA segments (RNA1: size 2.9 kb), impacting almost all organs and tissues of affected shrimp except for the hepatopancreas and eyestalks (Chen et al. 2021). Clinical manifestations of WTD-infected shrimp include lethargy, degeneration of the telson and uropods, and cloudiness in the abdominal muscle, with mortality rates reaching up to 100% within 4 days post-onset (Bonami and Widada 2011; Sahoo et al. 2024). The disease usually begins with localised lesions in the tail region, gradually spreading to the abdominal muscles and eventually resulting in widespread whitening of the muscle tissues, including those in the cephalothorax. In advanced stages, degeneration of the telson and uropods is commonly observed (Murwantoko et al. 2016; Bonami and Widada 2011).

Misuse of antibiotics and resistance development in shrimp aquaculture: limitations in viral disease management

Environmental factors such as temperature and salinity changes, excess nutrients, faecal pollution, toxic algal blooms, and residual antibiotics further complicate the situation by fostering the persistence and spread of resistant bacteria in shrimp pond ecosystems and nearby estuarine environments (Dalsgaard et al. 2000; DePaola et al. 2003; Konrad et al. 2017; Nongogo and Okoh 2014). In particular, *V. parahaemolyticus* has become a top concern because it is increasingly resistant to multiple antibiotic classes, limiting treatment options and leading to repeated outbreaks (Letchumanan et al. 2015). Numerous studies have reported finding antibiotic-resistant bacteria and associated antimicrobial resistance genes (ARGs) in shrimp aquaculture settings, water, pond sediment, and marketed shrimp, indicating widespread contamination and raising public health concerns (Harnisz et al. 2015; Naik et al. 2018; Pham et al. 2018; Tiedje et al. 2019; Fan et al. 2021; Chen et al. 2022). For instance, research in Vietnam's Mekong Delta identified 34 *V. parahaemolyticus* strains from shrimp affected by acute hepatopancreatic necrosis disease (AHPND), with many strains showing multidrug-resistant (MDR) profiles based on culture-dependent and PCR-based analyses. These findings highlight how extensive antimicrobial use promotes the formation of numerous antibiotic-resistant phenotypes (MARPs), which have significant implications for aquaculture productivity and biosecurity (Liu et al. 2017; Paul 2024; Wangkahart et al. 2025). Most shrimp farmers mistakenly believe antibiotics are useful during viral outbreaks. Since viruses such as WSSV, YHV, and Taura Syndrome Virus (TSV) cannot be treated with antibiotics, unlike bacteria, they provide no benefit and can instead lead to resistant bacteria (Akhila et al.2025; Ha et al. 2023). Additionally, using antibiotics during viral outbreaks can harm shrimp gut bacteria, weaken their immune systems, and delay the implementation of proper control measures. Prevention is better than a cure for viral diseases in shrimp. This involves using specific pathogen-free (SPF) broodstock, effective safety protocols, improving water quality, and incorporating supplements such as immunostimulants, probiotics, and prebiotics into their diet (Ha et al. 2023). Emerging technologies like RNA interference (RNAi) and bacteriophage therapy show promise, but they are not yet widely adopted in commercial aquaculture (Lee et al. 2022).

Environmental reservoirs of resistance

The aquaculture systems used for shrimp culture are increasingly recognized as important hotspots for the development and spread of antibiotic-resistant bacteria (ARB) and their associated resistance genes (ARGs) that pose great concerns for environmental integrity and aquaculture industry sustainability (Zheng et al. 2021). These systems consist of diverse ecological compartments such as water columns, sediments, and biofilms that provide conditions for the survival and adaptation of resistant populations of microbes. The repeated use of antibiotics, coupled with their release into the environment through aquaculture use, imposes intense selective pressure; hence the dominance of resistant strains. The conditions in the environment also enhance the possibility of horizontal gene transfer, particularly through mobile genetic elements such as plasmids, integrons, and transposons, which are responsible for the quick spread of resistance characters among microbial populations (Defoirdt et al. 2011). In addition, released residual antibiotics into aquatic environments are usually persistent and have limited degradation over time, further favouring the selection for resistance (Lu et al. 2018). Therefore, understanding the patterns of bioaccumulation of these chemicals in aquatic animals is critical in the evaluation of the potential health risks imposed on the farmed animals and the human consumers. Numerous studies have reported the quantification of antibiotic residues and ARGs in aquaculture organisms, with evidence of extensive antimicrobial contamination and emphasizing its importance for food safety and public health (Rosa et al. 2019; Yuan et al. 2019; Zhou et al. 2020, 2021).

Biofilm formation

Biofilm formation within shrimp aquaculture systems is crucial in shaping microbial community dynamics and has significant impacts on water quality, animal health, and production efficiency (Arunkumar et al. 2020). Biofilms are complex microbial communities embedded in an extracellular polymeric substance (EPS) matrix, which can be fixed on surfaces such as tank walls, aeration systems, pipes, and culture substrates. This organized environment provides a stable microenvironment conducive to colonization by a variety of microorganisms, including beneficial probiotics as well as opportunistic pathogens (Hossain et al. 2022). Promotive biofilms have been shown to have a key role in maintaining significant ecological processes such as nutrient cycling, organic matter degradation, and regulation of microbial homeostasis, processes that ultimately result in water quality and increased disease resistance in shrimp. Conversely, the very biofilm structures become repositories of pathogenic bacteria, including antibiotic-resistant strains. Such pathogenic biofilms are of interest, as they are likely to result in recurring disease outbreaks and compromise the efficacy of therapeutic interventions. Biofilms have also been described as central hubs for horizontal gene transfer, where exchange and storage of antibiotic resistance genes (ARGs) are facilitated by mobile genetic elements such as plasmids, transposons, and integrons (Wei et al. 2022).

Alternatives to antibiotics for viral disease control in shrimp aquaculture

Shrimp aquaculture has expanded, leading to the emergence and recurrence of viral diseases such as WSSV, YHV, and TSV. These viruses pose a serious health risk to shrimp and threaten their potential for healthy growth. Unlike bacterial diseases, we cannot treat these viral infections with antibiotics. Despite this, antibiotics are often used during viral outbreaks, causing issues like antibiotic resistance and environmental harm (Akhila et al. 2025; Ha et al., 2023). Overuse of antibiotics in shrimp farming has increased antimicrobial resistance (AMR) in aquatic environments. Residues of antibiotics in water and sediments can damage ecosystems and promote the spread of resistance genes among bacteria (Defoirdt et al., 2011; Hossain et al., 2022). To address these challenges, one promising approach is using probiotics and prebiotics, which improve gut bacteria balance, boost immune systems, and make it harder for pathogens to invade. When included in shrimp diets, these supplements have been shown to help shrimp resist both bacterial and viral infections (Ha et al., 2023). Beyond this, plant chemicals, especially from medicinal plants and essential oils, are gaining attention because they have antiviral, anti-inflammatory, and antioxidant properties. These compounds can inhibit virus growth, reduce stress during infection, and improve survival rates in virus-exposed shrimp. Additionally, advances in molecular biotechnology have introduced RNA interference (RNAi), a targeted approach that suppresses viral gene expression. Laboratory studies have demonstrated that RNAi can inhibit the replication of major shrimp viruses like WSSV. However, its use on farms is still being developed due to challenges in delivery and cost (Lee et al., 2022). Complementing these efforts, researchers are also exploring nanotechnology, which offers promising ways to fight viruses. Metal nanoparticles such as silver, zinc oxide, and selenium display strong antimicrobial activity. They have the potential to lower viral loads and enhance immune responses in aquatic animals. These nanoparticles can be delivered orally through feed or applied in water treatment systems to reduce virus transmission (Ha et al., 2023) (Fig. 1 and Table 2).

Figure 1. Comparative Overview of Antibiotic Alternatives in shrimp aquaculture

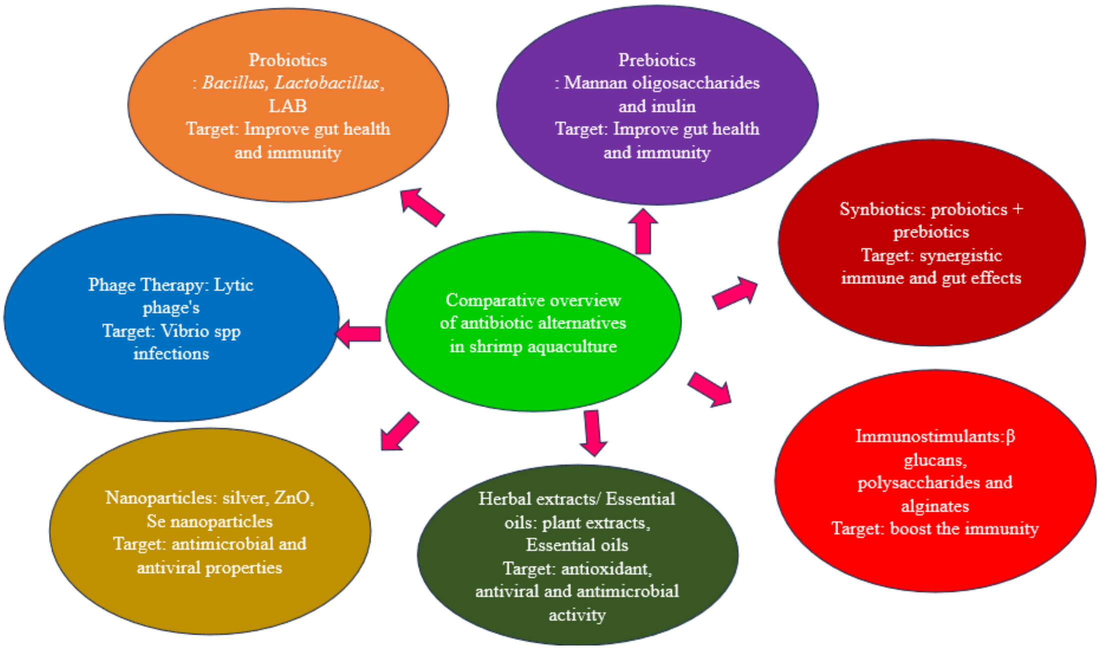


Figure 1: This schematic provides an improved and more visually structured overview of antibiotic alternatives in shrimp aquaculture. The diagram highlights seven major categories: probiotics, prebiotics, synbiotics, immunostimulants, nanoparticles, herbal extracts/essential oils, and phage therapy. Each category is presented with representative examples and their specific targets, such as enhancing gut health, boosting immunity, or providing antimicrobial and antiviral activity.

Table 2. Antibiotic alternatives used in shrimp farming

Antibiotic Alternative	Dosage	Administration	Period of Feeding Time (Duration)	Response	Reference
Probiotics	1-5 g/kg of feed	Incorporation in feed	4 weeks	Improvement in gut health, disease resistance, and growth performance	Calcagnile et al. (2024), Wang et al. (2008)
Prebiotics	0.1-1% of feed	Mixing with feed	6 weeks	Enhancement of beneficial gut microbiota, disease resistance, and growth	Amin et al. (2023)
Herbal Extracts	Varies: 0.05-0.2%	In addition to food or water	5 weeks	Enhancement of immune function, disease resistance, and growth	Saptiani et al. (2020a)

Immunostimulants	As per the manufacturer's instructions	Injection or oral	8 weeks	Enhanced immune response leading to disease prevention	Yang et al. (2021)
Essential oils	Varies: 100-500 ppm	Mixing with feed	7 weeks	Improvement in gut health, disease resistance, and growth performance	Galib et al. (2025)
Nano-particles	Varies: 0.1-1 mg/L	Addition to water or feed	6 weeks	Enhanced disease resistance, growth promotion, and water quality improvement	Vijayaram et al. (2021)

Probiotics, prebiotics, and synbiotics

Unlike bacterial infections, viral diseases cannot be controlled by antibiotics. Therefore, exploring non-antibiotic-based alternatives for treating viral diseases are essential for achieving sustainable shrimp production. Among the most promising alternatives are probiotics, prebiotics, and synbiotics, which modulate host immunity and enhance disease resistance through microbiota-mediated mechanisms. Probiotics and prebiotics have gained significant attention as viable strategies to combat viral and bacterial infections in shrimp farming, leveraging the beneficial effects of microorganisms to promote health and bolster disease resistance (Ringø 2020; Yarahmadi et al. 2022; Vijayaram et al. 2023). Probiotics, typically consisting of beneficial bacterial strains, and synbiotics, a combination of probiotics with prebiotics, have been shown to modulate immune responses, inhibit pathogenic colonization, and improve survival in virus-challenged shrimp (Amiin et al. 2023). Hai (2015) emphasized the efficacy of probiotics in improving the growth, survival, and viral disease resistance of aquatic organisms, including shrimp. Some probiotic genera such as Lactobacillus and Bacillus have demonstrated significant immunostimulatory and antiviral properties in shrimp (Amiin et al. 2023). Their mechanisms of action include competitive exclusion of pathogens in the gut and the production of bioactive compounds like organic acids, antimicrobial peptides, and enzymes that contribute to antiviral defences (Moriarty, 1999). Lactic acid bacteria (LAB), such as *Lactiplantibacillus plantarum*, and spore-forming bacteria, such as *Bacillus subtilis*, are among the most extensively studied probiotics in shrimp aquaculture. These strains enhance host immunity by producing antimicrobial metabolites, such as lactic acid, bacteriocins, hydrogen peroxide, short-chain fatty acids, and exopolysaccharides, that promote gut health and suppress both bacterial and viral pathogens (Ayivi et al. 2020). The use of commercial probiotic formulations like PowerShrimp™ (QB Labs) has demonstrated practical benefits in shrimp culture, including improved immune response and gut integrity, which are critical in defending against viral infections (Butt et al. 2021). Criteria for selecting probiotic candidates include their ability to tolerate environmental stressors, colonize the host gut, exhibit antiviral and antimicrobial activity, and avoid transmitting antibiotic resistance genes (Al-Shawi et al. 2020; Labba et al. 2020). Numerous studies have reported immunostimulatory effects of probiotics specifically against viral infections. For instance, the administration of *Bacillus cereus and Pediococcus acidilactici* in shrimp rearing water increased lysozyme activity and total hemocyte count, key indicators of antiviral innate immunity (Khademzade et al. 2020). Similarly, *Staphylococcus haemolyticus* and *Pediococcus pentosaceus* strains isolated from wild shrimp demonstrated protective effects against *Vibrio* species and improved survival of shrimp experimentally infected with WSSV (Leyva-Madrigal et al. 2011). In addition, sediment-derived probiotic strains such as *Streptomyces fradiae* and *Bacillus megaterium* have shown effectiveness in improving water quality and reducing mortality in black tiger shrimp, indirectly supporting antiviral defence by lowering environmental stress (Aftabuddin et al. 2013). The integration of prebiotics, non-digestible carbohydrates such as oligosaccharides, inulin, and dietary fibers, into shrimp feed has been shown to stimulate beneficial gut microbiota and improve mucosal immunity (Huynh et al. 2018a). The combination of probiotics and prebiotics as synbiotics offers synergistic benefits for antiviral protection. This strategy enhances nutrient absorption, immune modulation, and resistance to viral infections. However, despite their potential as sustainable alternatives to antibiotics, several challenges remain in applying these biological agents at a commercial scale. These include maintaining probiotic viability, functional consistency under variable environmental conditions, and ensuring cost-effectiveness. Future advancements in microencapsulation technologies and targeted delivery systems may help overcome these obstacles and improve the efficacy of probiotics and prebiotics in virus control (Ringø et al. 2020).

Immunostimulants and vaccines

Bioactive immunostimulants of natural and synthetic origin are increasingly recognized as effective, sustainable alternatives to antibiotics in modern shrimp aquaculture, especially for controlling viral diseases like WSSV, YHV, and IMNV. These compounds can come from various sources, including botanical, zoological, microbial, and synthetic origins, and are typically classified into macromolecules (such as proteins, lipids, nucleic acids, and polysaccharides) and low-molecular-weight compounds like phytochemicals and microbial metabolites (Šimat et al. 2020; Kumar et al. 2022). They exhibit a broad spectrum of bioactivities, including antioxidant, antimicrobial, anti-inflammatory, cytotoxic, chemotactic, antitumor, antifouling, and apoptosis-regulating effects, all of which enhance shrimp immunity and reduce the pathogenicity of viral infections (Roy 2020; Yang et al. 2021; Vijayaram et al. 2022, 2023). The mechanisms of action for immunostimulants involve activating innate immune responses by interacting with pattern recognition receptors, such as β-glucan receptors and dectin-1 on shrimp haemocytes. This interaction triggers signaling pathways, especially the NF-κB pathway, leading to the transcription of immune-related genes and the activation of protective enzymes like phenoloxidase, lysozyme, and superoxide dismutase, which play critical roles in antiviral defence (Brown and Gordon 2002; Sun et al. 2019). Numerous plant-derived immunostimulants, like *Astragalus* polysaccharides (APS), chlorogenic acid (CGA), and berberine (BBR), have demonstrated effectiveness in modulating nonspecific immune markers and exhibiting antiviral activity against WSSV by enhancing haemocyte function and decreasing viral load in infected shrimp (Chang et al. 2018; Ghosh et al. 2021; Nolasco-Alzaga et al. 2025). Beyond direct immunostimulation, combining probiotics and prebiotics has proven to be an effective strategy for preventing viral diseases. Prebiotics like mannan oligosaccharides (MOS) and xylooligosaccharides (XOS) serve as fermentable substrates that bolster beneficial gut microbiota, thereby further enhancing immune responses and gut health (Calcagnile et al. 2024; Ringø et al. 2020). These effects have been observed with the supplementation of Bio-Mos® and β-1,3-D-glucan, which improved growth and immune competence in western king prawn (*Penaeus latisulcatus*), as well as increased survival of whiteleg shrimp under environmental stress, likely due to immune enhancement and resistance to viral challenges (Van Hai and Fotedar 2009; Gatlin et al. 2006). Dietary XOS has also improved feed conversion efficiency and stimulated the expression of immune genes, aiding in resistance against viral pathogens (Yousefian and Amiri, 2009). Another emerging approach involves oral administration of inactivated pathogen biofilms, such as *V. harveyi* cultured on chitin substrates. These biofilms, rich in pathogen-associated molecular patterns, provoke strong antiviral immune responses when given orally, functioning as immunostimulants or vaccine-like agents against WSSV (Sharma et al. 2010; Mamun et al. 2019; Vinay and Sahu 2019). Overall, these alternative strategies, including immunostimulants, probiotics, prebiotics, and inactivated biofilm-based products, offer promising avenues to reduce viral disease impact in shrimp farming. Their effective use supports the global movement away from antibiotics and provides sustainable, eco-friendly options to improve shrimp health and productivity (Nolasco-Alzaga et al. 2025).

Phytobiotics

Phytobiotics are naturally occurring biomolecules present in or extracted from plants, including herbal extracts, EOs, and isolated bioactive molecules. Herbal extracts and EOs of medicinal herbs are increasingly being used as environmentally safe and effective alternatives to synthetic antibiotics in shrimp aquaculture, especially for the control of viral diseases like WSSV and *Enterocytozoon hepatopenaei* (EHP) (Tu et al. 2023; Vijayaram et al. 2016). Phytobiotic compounds have wide-ranging bioactivity, from antimicrobial, antiviral, antioxidant, and immunostimulatory activities, and can be used as dietary supplements or topical treatments to improve shrimp health and resistance. Phytobiotics like phenolics, flavonoids, tannins, terpenoids, and essential oils are highly desired due to their immunomodulatory and antimicrobial properties (Kengkittipat et al. 2025). Several studies have demonstrated the disease-preventive and immune-enhancing capabilities of several herbal extracts in shrimp. For example, mangrove plant leaf extracts of *Xylocarpus granatum* significantly improved the viability of *V. harveyi*-infected shrimp by an increase in circulating haemocyte counts, indicating the immunostimulatory action of the extract (Sengupta and Mukherjee, 2025). Likewise, *Theobroma cacao* pod husk extract injection induced upregulation of the key immune genes TLR-1, STAT, and crustin, illustrating its capacity to induce host defence mechanisms (Lee et al. 2020). Of specific interest to viral disease management, Olea europaea (olive) leaf extract improved survival by 65% in WSSV-infected shrimp, whereas the phytogenic blend Phytocee™ (with *Emblica officinalis*, *Ocimum sanctum*, and *Withania somnifera*) combined with ascorbic acid monophosphate significantly improved shrimp survival against WSSV challenge (Pet et al. 2025; Selvam et al. 2020). Marine-derived plant compounds also have promising antiviral activity. The fucoidan isolated from *Sargassum polycystum* displayed antiviral activities, while a methanol extract of five medicinal plants (*Cynodon dactylon, Aegle marmelos, Tinospora cordifolia, Picrorhiza kurroa, and Eclipta alba*) yielded a survival of 74% in WSSV-infected shrimp when fed at a dietary inclusion of 800 mg/kg (Galib et al. 2025). Other studies have demonstrated that *A. marmelos, C. dactylon, Lantana camara, Momordica charantia*, and *Phyllanthus amarus* possess antiviral activities (Md Ashiq et al. 2025). Applying chitosan and mangrove flour has also been associated with reduced mortality due to WSSV (Manik et al. 2020). Novel delivery systems, for instance, the delivery of *Sonneratia alba* (Mangrove Apple) fruit extract via Artemia salina nauplii, have managed to defend shrimp against *V. harveyi* infection, demonstrating that oral bioencapsulation is an effective delivery system to apply for the delivery of herbal antiviral drugs (Cahyadi et al. 2020). Well-known herbs such as *Citrus limon, Allium sativum, Zingiber officinale, Borassus flabellifer,* and *Vigna mungo* possess activity against EHP, the causative agent of white faeces syndrome (WFS), in semi-intensive whiteleg shrimp production systems (Palanikumar et al. 2020). These phytobiotics can boost the immunity of shrimp and combating parasites, hence making them less susceptible to WFS and other viral diseases. Apart from combating viruses, most of these herbal drugs also possess antioxidant and anti-stress activities. Rutin, a flavonoid extracted from traditional Chinese medicine plants, for example, has been shown to aid shrimp in stress coping (Cortez-Mago et al. 2025). Chinese herbs have been extensively researched for their immune-enhancing capabilities; recent work by Yin et al. (2023) demonstrated that supplementation with *Psidium guajava* leaf powder considerably enhanced major immune enzyme activities such as SOD, PO, ACP, AKP, and lysozyme in shrimp. In another experiment, supplementation of shrimp with methanolic extracts of five Chinese herbs for 25 days before a WSSV test suppressed virus growth and enhanced survival by boosting blood health and immunity (Galib et al. 2025).

Nanoparticles

Nanoparticles are ultrafine particles between 1–100 nm. Because they have unique physicochemical properties, such as increased surface area, high reactivity, and enhanced bioavailability, these particles differ significantly from their bulk counterparts. Consequently, they are useful in aquaculture for applications like targeted drug delivery, antimicrobial activity, and feed supplementation. Recent research has shown that dietary feeds enhanced with nanomaterials, including copper, selenium, magnesium, manganese, iron, zinc, chromium, and chitosan, effectively substitute for antibiotics by improving the health and disease resistance of aquatic animals (Vijayaram et al., 2021; Vijayaram et al., 2023; Ghafarifarsani et al., 2024). By incorporating nano-formulated feed additives, aquaculture practitioners have observed improvements in gut microbiota composition, growth performance, survival rates, immunological responses, antioxidant capacities, digestive enzyme activities, feed intakes, feed conversion ratios, and nutrient bioavailability. These developments take on greater significance in managing viral infections in shrimp farming, since conventional chemotherapeutic approaches are often ineffectual or unsustainable. Of all the nanomaterials used, silver nanoparticles (AgNPs) attract particular attention due to their strong antiviral and broad-spectrum antibacterial activities (Vijayaram et al. 2024). Considered promising candidates for preventing and controlling viral pathogens like WSSV and other emerging viral threats in shrimp aquaculture, AgNPs disrupt several stages of viral infection cycles for example, viral attachment, cell penetration, and replication (Elechiguerra et al. 2005). Their antifungal action, especially against *Candida* spp., further supports their utility in treating fungal co-infections often linked to immune suppression during viral outbreaks (Gajbhiye et al. 2009). Studies have additionally shown that AgNPs inhibit *Plasmodium* spp., which suggests a possible role in managing parasite disorders capable of worsening viral infections in aquaculture systems (Saravanan et al. 2017).

Biosecurity measures and management practices

Biosecurity involves a broad array of practices conducted at any farm and regional levels that seek to reduce the risk of aquatic animals acquiring, carrying, or transmitting infectious agents and other negative health conditions (Bhassu et al. 2024; Othman et al. 2024). For shrimp farming, the highest-risk farms for disease outbreak must be alerted to the risk of poor biosecurity, as well as the advantages of active disease management, such as the reduction of the spread of pathogens to neighbouring facilities. Strengthening biosecurity practice is critical for long-term shrimp farming sustainability, especially because crustaceans lack adaptive immunity, hence making conventional disease control measures such as vaccination irrelevant (Walker and Mohan, 2009; Ali et al., 2018). The growing global interest in reducing the use of antibiotics in aquaculture and the effect on environmental as well as public health has driven increased focus towards more sustainable disease control measures. Among the measures, strong biosecurity is a key component in the prevention of infectious disease outbreaks as well as reducing antibiotic reliance (Seyfried et al., 2020). Correspondingly, optimal water quality maintenance is critical to shrimp health, as environmental stressors have the capability to impair innate immune functions and increase susceptibility to opportunistic pathogens. Regular monitoring of critical water quality parameters, such as dissolved oxygen, temperature, pH, and ammonia, is crucial for timely identification of stressors as well as immediate implementation of correction measures (Seyfried et al., 2020).

Economic implications and cost–benefit analysis

Inclusion of probiotics, phytobiotics, nanoparticles, and phage therapy in shrimp culture involves diverse economic as well as biological considerations. Although the initial costs involved with them may exceed those of conventional use of antibiotics, the long-term benefits they present bring huge economic returns.

Probiotics and phytobiotics: Supplementing feed with probiotics or plant-derived bioactive compounds has been proven effective for stimulating growth and development, enhancing feed conversion ratio, and improving survival of shrimp. These beneficial effects yield higher production levels coupled with lower mortality rates from disease and hence compensate for the supplementary costs, 3-10 dollars per ton feed. Further, reduction of reliance on antibiotics is consistent with sustainable production of aquatic animals as well as mitigating economic uncertainties from antimicrobial resistance.

Nanoparticles: Nanoparticle strategies like targeted delivery of antimicrobial agents may prove more expensive to make and formulate. However, by their high efficiency at lower dosages, enhanced bioavailability, and their potential to reduce pathogen burdens, overall disease management costs could be reduced. Economies of scale and tech optimisation will bode well for increased cost-effectiveness for commercial production.

Bacteriophage therapy: Phage treatments offer an extremely selective and environmentally friendly alternative to conventional use of antibiotics. Although phage production and formulation impose additional costs, selective phage activity against pathogenic bacteria offers the promise of reducing disease-related losses while focusing the use of broad-spectrum antimicrobials, improving the profitability of the farm.

Conclusions

The shift away from antibiotic use in shrimp aquaculture is gaining considerable attention as a crucial necessity due to growing concerns about antimicrobial resistance, environmental pollution, and public health risks. The indiscriminate and prolonged use of antibiotics is linked to harmful effects on shrimp health, disruption of aquatic ecosystems, and the emergence of multidrug-resistant pathogens. As a result, the industry is actively pursuing safer and more sustainable alternatives for disease prevention and health management. One key approach involves strengthening biosecurity measures at both the farm and regional levels. Routine practices such as rigorous disinfection protocols, maintaining cleanliness, and carefully monitoring water quality are essential for minimising pathogen exposure and preventing disease outbreaks, thereby reducing reliance on antibiotics. Concurrently, science-based alternatives are becoming increasingly vital. These methods include utilising probiotics and prebiotics to improve gut health and inhibit pathogens, along with herbal extracts and plant compounds that possess potent antimicrobial and immunomodulatory properties. Immunostimulants from microbial, plant, and synthetic sources offer additional protection by boosting shrimp's innate immunity. Emerging technologies like nanoparticle-based treatments and inactivated biofilm therapy are also being developed as eco-friendly options aimed specifically at targeting infectious agents without harming non-target organisms or the environment. These combined strategies not only diminish antibiotic dependence but also bolster shrimp resilience to stress and disease, thereby enhancing overall production efficiency and sustainability. Successful implementation of these strategies requires coordinated efforts among farmers, scientists, and policymakers to ensure education, practical application, and regulatory support. Adopting these alternatives represents a forward-thinking shift toward a responsible, productive, and environmentally sustainable shrimp aquaculture model.

Author contributions

Srirengaraj Vijayaram and Einar Ringø: Conceptualisation; writing – original draft; Writing – review and editing, literature search; table preparation. Krishna Prakash Arunachalam: Writing, review, and editing. Ehsan Ahmadifar: Writing, review, and editing. Jeganathan Arun: Writing – review and editing. Hary Razafindralambo and Yun-Zhang Sun: Writing, review, and editing; supervision.

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Data availability statement

The findings supporting this research are expected to be made available upon the author's inquiry

Conflicts of interest

The authors declare no conflicts of interest.

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