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Research Article

Understanding the role of stress factors in disease incidence in shrimp aquaculture: A mini review

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Abstract

Stress in shrimp, triggered by environmental and management factors, increases susceptibility to pathogens and disease outbreaks, posing a major challenge to aquaculture. This review examines the interrelationship between stress and disease in shrimp farming, emphasizing stress management as a vital component of disease prevention. Shrimp in open farms encounter numerous stressors, including temperature and pH fluctuations, salinity changes, organic and suspended solids accumulation, overcrowding, hypoxia, and increased hydrogen sulfide, and nitrogenous compounds. Heavy metals, algal blooms, bacterial overload, pesticides, poor nutrition, feed issues, molting problems, and parasites also jeopardize shrimp health and productivity. This review outlines a comprehensive framework to manage stress and disease by keeping stressors within tolerable limits and by implementing appropriate mitigation strategies where feasible. It advocates for proactive stress control through suitable management practices and the application of appropriate technologies during shrimp rearing to sustain health and optimize productivity. Key strategies include maintaining water quality, optimizing stocking density, and closely monitoring environmental and biological stress indicators. By emphasizing regular health monitoring and early disease detection, this approach can preemptively address potential outbreaks, reducing their impacts on shrimp stocks and farm economics. This review provides an in-depth analysis of stress-disease dynamics in shrimp aquaculture, guiding farmers to create resilient, disease-resistant, and sustainable farming operations.

Introduction

The shrimp farming sector is experiencing rapid global expansion. Today, it not only fulfills a substantial portion of global human protein requirements but also significantly shapes the economic landscape of aquaculture. Currently, shrimp farming is playing a crucial role in meeting the rising demand for seafood (Kazuń *et al*., 2019). According to the Global Seafood Alliance's annual Global Shrimp Aquaculture Production Survey and Forecast report, the world's production of farmed shrimp in 2023 was projected to decline slightly (by 0.4 percent) to approximately 5.6 million metric tons (Villarreal, 2023). The top five shrimp-producing countries in 2023 are projected to be Ecuador, China, India, Vietnam, and Indonesia, collectively accounting for approximately 74% of global production. Additionally, other significant producers in Asia and Latin America are anticipated to contribute around 840,000 metric tons (MT) and 500,000 MT, respectively, to the world's shrimp production in 2023. The Global Seafood Alliance's report forecasts a modest decline in industry supply of about -0.4 percent in 2023, followed by a more optimistic outlook for 2024 with an expected growth rate of approximately 4.8 percent (Jory, 2023) .

Currently, shrimp farming worldwide predominantly relies on semi-intensive and intensive monoculture systems. In many cases, inexperienced shrimp farmers often increase stocking density per square meter without making necessary infrastructural and management adjustments when transitioning from semi-intensive to intensive systems (Pazir *et al*., 2022). The development of this industry is significantly influenced by various factors, encompassing both biological and abiotic elements. Biological factors such as genetics, age, and overall health play a pivotal role, while abiotic factors like environmental conditions, stress levels, and resource availability also contribute to overall production performance. It is imperative for shrimp farmers to carefully monitor and manage these factors to achieve optimal production levels and ensure long-term sustainability. Through the adoption of best practices in shrimp rearing, nutrition, disease management, environmental control, and biosecurity, the industry has the potential to continue evolving and to meet the growing global demand for high-quality shrimp products (Deepthi *et al*., 2024).

Stress in shrimp, akin to its manifestation in other organisms, is a natural response to environmental or physiological changes that disrupt normal physiological functions. This stress reaction initiates a sequence of hormonal and metabolic adjustments that enable shrimp to cope with adverse conditions. The release of stress hormones during periods of stress can negatively impact the shrimp's immune system, thereby rendering it more susceptible to pathogens and increasing the likelihood of disease outbreaks (Millard *et al*., 2021). Furthermore, stress can disrupt key physiological processes, such as metabolism and growth, leading to decreased survival rates and reduced feed intake. This, in turn, may result in nutritional imbalances and deficiencies, further compromising the immune system and increasing susceptibility to diseases. Common stressors affecting shrimp in aquaculture systems include poor water quality, overcrowding, sudden changes in temperature or salinity, inadequate feeding, and the presence of aggressive tank or pond inhabitants (Chen and He, 2019; Ren *et al*., 2021). Effective management of these stressors is therefore essential for maintaining the health and productivity of shrimp populations.

This review aims to explore the factors contributing to stress and disease in shrimp farms, as well as the strategies available to manage these challenges throughout the culture cycle. It represents one of the early comprehensive attempts to synthesize current knowledge on this topic. Moreover, the importance of routine monitoring and early disease detection cannot be overstated, as these practices can help prevent disease outbreaks and reduce their impacts on shrimp production systems. By adopting these strategies, shrimp farmers can create a healthier culture environment and enhance the productivity and sustainability of shrimp farming operations.

Shrimp immune system

Invertebrates, such as shrimp, possess a relatively less complex immune system that lacks the high degree of specificity typically observed in vertebrate adaptive immunity. This non-specific immune system often requires stimulation through immunostimulants to enhance the organism's defense mechanisms against pathogens. Consequently, to reduce the increased susceptibility of shrimp to stress and disease, these substances are often used as dietary supplements during the rearing period (Smith, 2010). Shrimp have a system called "immune priming" that prepares their immune system for future encounters with pathogens. This is facilitated by molecules such as Dscam (Down syndrome cell adhesion molecule), which suggests the presence of a memory-like response within the innate immune system. This discovery creates new opportunities for developing strategies that enhance targeted immune responses in shrimp, potentially reducing their vulnerability to diseases (Li *et al*., 2019). By improving the application and effectiveness of immunostimulatory compounds, the industry can mitigate the risks associated with disease outbreaks (Flegel, 2019) (Table 1).

Table 1: Compare the immune systems of vertebrates and invertebrates.

Characteristics	Vertebrates	Invertebrates
Antibodies	✓	×
Memory cell	✓	×
Lymphocyte cells	✓	×
Cytokines	✓	✓
Lectins	✓	✓
Clotting mechanism	-Fibrin based mechanism	Not Fibrin based mechanism
killing cells	✓	✓
Phenol oxidase system	No Phenol oxidase	Phenol oxidase and Melanin

Stress in shrimp

Stress definition

Stress represents an organism's response to environmental variables, enabling it to adapt or respond to environmental changes. In essence, stress is a double-edged sword for organisms, capable of both fostering resilience and causing harm. Therefore, any external or internal stimulus that disrupts physiological equilibrium is considered stress. Generally, stress can be both beneficial and harmful. In its positive form, it can promote adaptation, evolutionary advancement, and improved survival. Conversely, in its negative form, stress can severely impair an organism's physiological functions and immune defense against pathogens. Thus, stress is an inherent component of biological systems, making a completely stress-free life virtually impossible (Chen and He, 2019).

Stress symptoms in farmed shrimp

Shrimp farming stress can cause various physiological responses such as lethargy, reduced feeding, slow growth, molting disorders, abnormal behaviors, and even mortality. One of the most important physiological indicators of stress in shrimp is an elevation in hemolymph glucose levels, and evaluating the shrimp’s osmoregulatory capacity is also a useful indicator for assessing stress intensity. Research has shown that stressors such as ammonia and hypoxia can significantly affect shrimp health, leading to hyperglycemia and alterations in the total hemocyte count (THC) following ammonia exposure (Schock *et al*., 2013). Similarly, hypoxia can impair osmoregulatory function and increase glucose and lactate concentrations in the hemolymph, indicating a metabolic response to low oxygen conditions (Martínez-Antonio *et al*., 2019). Additionally, chronic stressors such as low salinity may reduce the shrimp's capacity to cope with subsequent acute stress events, thereby further complicating their physiological and metabolic responses (Zhu *et al*., 2024).

Stress stages in shrimp

Shrimp experience three distinct stages of stress: alarm, adaptation (resistance), and exhaustion or injury. During the alarm stage, despite elevated levels of anti-stress hormones within their bodies, shrimp generally do not exhibit obvious external signs. In the adaptation (resistance) stage, shrimps employ various physiological and behavioral strategies to mitigate the effects of stressors, either by adjusting their metabolism or by avoiding unfavorable environmental conditions, depending on the nature of the stress. This stage is characterized by increased energy expenditure, which may manifest as reduced feeding activity, lethargy, and slower growth rates. If the stressor persists, shrimp progress to the exhaustion or injury stage, which is marked by significant mortality and severe physiological damage, including irreversible impairment of certain sensory and physiological functions. Moreover, stress can impair the shrimp's molting process, making them more susceptible to shell diseases and opportunistic infections (Wang *et al*., 2022). Intensive and semi-intensive aquaculture systems can further intensify stress in shrimp due to a combination of environmental and management-related factors. The presence of opportunistic pathogens under such stressful conditions can further weaken shrimp and lead to population declines, ultimately resulting in disease outbreaks (Martínez-Antonio *et al*., 2019).

Mechanisms of stress in shrimp

Several mechanisms explain how stress affects shrimp physiology and immunity. The primary pathway involves an increased release of stress-related hormones, which can compromise the immune system by reducing the production and activity of immune cells such as hemocytes, thereby rendering shrimp more susceptible to infections (Zhu *et al*., 2024). In addition, stress can alter and disrupt the composition of the gut microbiota (a condition known as dysbiosis), which weakens immune function and increases the risk of disease (Dai *et al*., 2018; Xiong *et al*., 2024). Furthermore, stress can induce oxidative stress in shrimp, disrupting the balance between reactive oxygen species (ROS) production and the shrimp's antioxidant defense mechanisms. This imbalance can lead to cellular and tissue damage, impair immune responses, and increase susceptibility to diseases (Wang *et al*., 2024). Additionally, stress can affect the function of immune-related organs, such as the hepatopancreas, a key organ involved in metabolism and immune regulation in shrimp (Lu *et al*., 2016). On the other hand, certain proteins, notably heat shock proteins (HSPs), are strongly induced in shrimp under various stress conditions, including viral infections, hypoxia, and handling. These proteins, which are highly conserved across species, act as molecular chaperones that assist in protein folding, assembly, stabilization, and degradation (Yingsunthonwattana *et al*., 2022; Pourmozaffar *et al.***,** 2023). Specific HSPs identified in shrimp include:

- HSP40: Functions as a co-chaperone for HSP70 and facilitates the regulation of ATP hydrolysis during protein folding processes.
- HSP70: Plays a key role in the innate immune response of shrimp and is significantly upregulated during infections with white spot syndrome virus (WSSV).
- HSP90: Is involved in cellular stress responses and has been reported to facilitate WSSV replication, with its expression increasing following WSSV infection.

The function of shrimp hormones in stressful conditions

Stress can disrupt the balance of neurotransmitters within the shrimp's nervous system, thereby affecting their behavior and immune responses. Neurotransmitters such as dopamine and serotonin are crucial for regulating shrimp behavior and immune function. Stress can alter the levels of these neurotransmitters, leading to behavioral changes and impaired immune competence (Tong *et al*., 2022). Dopamine plays a crucial role in regulating shrimp physiology during stress by modulating energy metabolism, osmoregulation, respiration, and acid-base balance. While it does not directly influence behavior to the same extent as serotonin, its physiological effects may indirectly influence behavior through interconnected neuroendocrine pathways. For example, elevated dopamine levels under stress conditions have been associated with suppressed immune responses, thereby increasing susceptibility to stressors (Lu *et al*., 2016)

Serotonin (5-HT) is an important hormone involved in the regulation of stress responses and behavior in shrimp. Stressors can disrupt serotonin balance, leading to behavioral alterations and reduced immune efficiency. For instance, serotonin stimulates ovarian maturation and spawning in black tiger shrimp; however, elevated serotonin levels may also enhance sensitivity to environmental stressors. Serotonin additionally affects feeding behavior and overall activity levels in shrimp (Rahi *et al*., 2021).

The interaction of variables affecting shrimp health

Shrimp health is influenced by various interrelated factors, including genetic makeup, species, life cycle, stocking density, environmental conditions, and physiological characteristics. These factors interact dynamically with one another, creating a multifactorial and bidirectional network of influences that is crucial for maintaining shrimp health (Millard *et al*., 2021).

1. Environmental conditions: Elevated water temperatures can induce stress in shrimp, thereby increasing their susceptibility to diseases. Conversely, shrimp with compromised immune systems, whether due to genetic predisposition, suboptimal nutrition, or chronic stress, may be particularly vulnerable to thermal stress (Millard *et al*., 2021; Ren *et al*., 2021).
2. Physiological and water quality factors: Key water quality parameters, such as dissolved oxygen, pH, and salinity, significantly influence shrimp growth, metabolism, and immune function. Fluctuations or deviations from optimal ranges in these parameters can induce stress and impair immune responses (Ario and Nursani, 2024).

Understanding and effectively managing these interconnected factors is essential for optimizing shrimp health and enhancing productivity in aquaculture systems (Fig. 1).

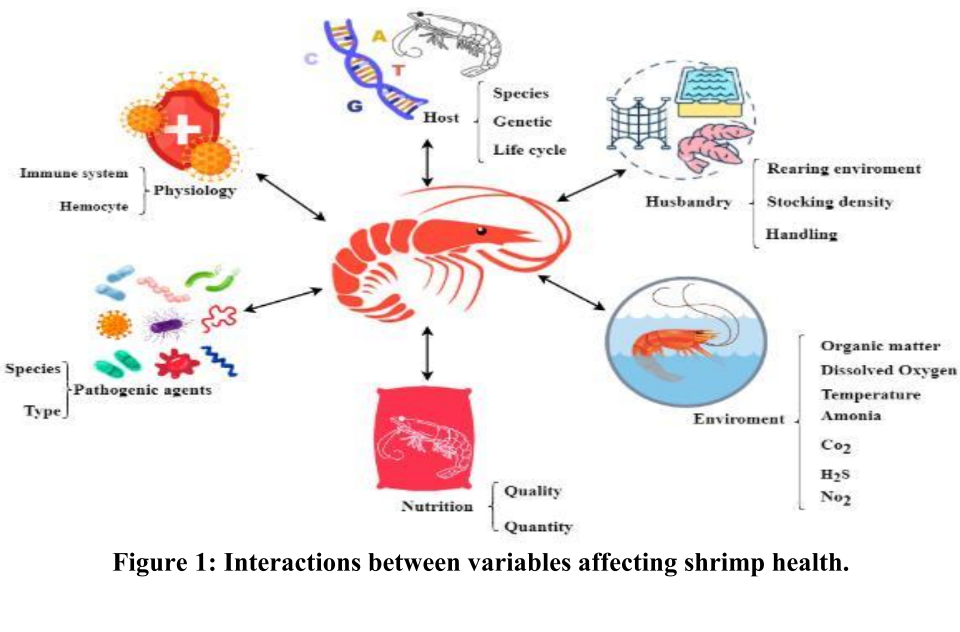

Figure 1: Interactions between variables affecting shrimp health.

Stress management

Outdoor shrimp farming systems face significant challenges, particularly fluctuations in water temperature that threaten shrimp health. One effective strategy to mitigate water temperature variations during hot seasons is increasing the pond water depth to approximately 2.5–3 meters. In addition, the use of aeration devices such as paddlewheel aerators, air jets, diffusers, or venturi aerators is recommended to enhance vertical water mixing, prevent thermal stratification, and maintain a more uniform water temperature during periods of intense daytime heat (Bartlett and Dedekorkut-Howes, 2023; Villarreal, 2023). Another critical challenge in shrimp farming is fluctuation in pond water pH, which is often associated with algal blooms. These blooms can lead to reduced dissolved oxygen levels during nighttime due to increased respiration by aquatic organisms and the release of carbon dioxide from phytoplankton. Therefore, effective water quality management and the control of excessive algal growth are essential to maintain adequate dissolved oxygen levels and ensure a stable culture environment (Lyu *et al*., 2021). The decomposition of organic matter at the bottom of shrimp ponds consumes significant amounts of oxygen, which can lead to hypoxic conditions, particularly between the 60th and 70th days of the culture cycle. This oxygen depletion can subsequently trigger disease outbreaks and shrimp mortality (Iber and Kasan, 2021) (Fig. 2).

Figure 2: The reduction of feeding in shrimp ponds, particularly due to the accumulation of organic matter at the pond bottom.

To address this, it's recommended to remove accumulated sludge ("black soil"), plow the pond bottom, apply lime, and use oxidizing agents during pond preparation to facilitate the degradation of accumulated organic matter. During the rearing season, the use of a central drainage system can help prevent the accumulation of these waste materials (Boyd, 1990, 2016; Iber and Kasan, 2021). Additionally, insufficient feeding can slow shrimp growth, prolong the culture period, and make shrimp more vulnerable to pathogens. Conversely, overfeeding leads to the accumulation of uneaten feed and organic matter at the pond bottom, thereby increasing the risk of disease. Therefore, effective feed management is essential, taking into account shrimp nutritional requirements, survival rates, feed quality, stocking density, pond carrying capacity, and the appropriate use of equipment such as aerators and automatic feeders (Niu *et al*., 2016).

Disease outbreak

According to Snieszko's epidemiological model, diseases in shrimp farms result from the dynamic interaction between the shrimp (host), pathogens, and the environment. Factors such as stocking density, shrimp genetics, and the quality of water and feed contribute to disease outbreaks (Said *et al*., 2024). These factors act as stressors that can facilitate infections when pathogens are present. Under controlled conditions, or where pathogens are absent, the use of specific pathogen-free (SPF) or specific pathogen-resistant (SPR) shrimp, the minimization of rearing disturbances, the provision of proper nutrition, consistent water quality maintenance, and the control of algal blooms can effectively prevent disease (Pazir *et al*., 2022) (Fig. 3).

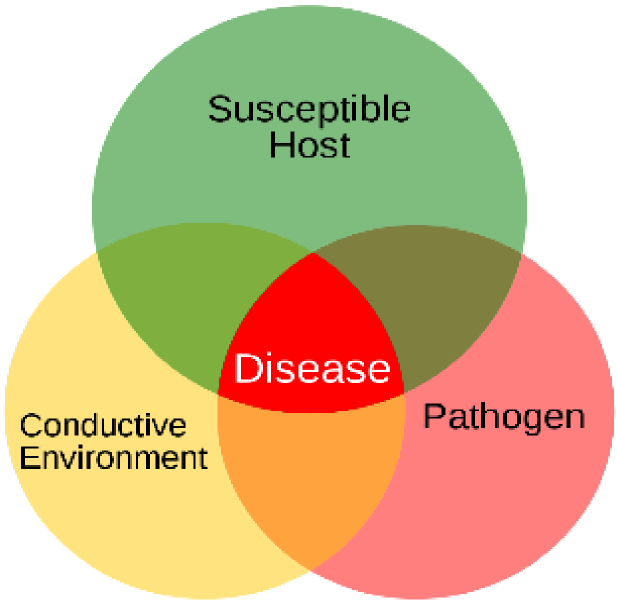

Figure 3: Disease outbreak: interaction between the host (shrimp), the pathogenic agent, and the environment.

However, poor feed quality, improper feeding practices, algal blooms, low oxygen levels, and pH fluctuations can cause non-infectious diseases in shrimp ponds. To prevent both infectious and non-infectious diseases, it is essential to minimize environmental and management-related stress on shrimp during the rearing cycle, as stress weakens their immune system and increases susceptibility to disease. Creating a favorable, stress-minimized environment and providing proper nutrition and care can significantly reduce disease risks in shrimp farming (Neuhouser, 2019) (Table 2).

Table 2: The role of factors influencing disease outbreaks in shrimp aquaculture based on Sneath's model.

Aspect	Details	Sources
Domestication and Genetic Structure (Host)	Domestication enhances genetic structure in *Litopenaeus vannamei*, improving uniformity and stress resilience. Selective breeding increases disease resistance, particularly against TSV and IHHNV. Different families show varying susceptibilities.	(Nguyen, 2024; Ren *et al*., 2025)
Pathogens in Shrimp Farming	Pathogens are categorized as obligatory or opportunistic. Most are opportunistic, thriving in stressed hosts. Bacterial pathogens weaken hosts, facilitating secondary infections. WSSV and YHV are among the most lethal.	(Robinson *et al*., 2023)
Environmental Conditions	Environmental factors like temperature, salinity, pH, and water quality significantly influence shrimp health. Stressors like elevated ammonia and low oxygen increase disease susceptibility. Effective management is essential.	(Gutiérrez-Pérez *et al*., 2022; Shan *et al*., 2025)

The interaction between environmental conditions and disease incidence

Temperature and disease incidence in shrimp

Temperature is a critical environmental factor that significantly affects shrimp health due to their ectothermic nature. As ectotherms, shrimp rely on external temperatures to regulate their body heat, making them particularly sensitive to environmental temperature fluctuations. Exposure to temperatures outside their optimal range can disrupt normal physiological processes, induce stress, and compromise their health and survival. Shrimp can tolerate a broad temperature range, from 7.5°C to 42°C (Millard *et al*., 2021). However, significant deviations or rapid fluctuations in temperature can greatly influence their physiology, immune function, and stress levels. Optimal temperatures for shrimp growth vary depending on species and life stage. Generally, shrimp tend to grow faster at relatively higher temperatures; however, once temperatures exceed the optimal threshold, mortality rates begin to increase. For example, smaller shrimp generally perform better at temperatures above 30°C, while larger shrimp tend to perform optimally at around 27°C. The ideal temperature range for maximum yield is typically between 26–30°C, which provides a balance between rapid growth and high survival rates. Temperatures above 32°C have been reported to reduce survival rates and increase health risks in cultured shrimp (Wyban *et al*., 1995). Extreme temperatures can stress shrimp, leading to physiological and behavioral changes. High temperatures can reduce feed intake, impair growth performance, and increase mortality rates, while low temperatures decrease metabolic activity, slow growth, and weaken immune responses. Rapid temperature fluctuations can further disrupt shrimp's physiological processes and immunity, although shrimp are generally capable of adapting to gradual temperature changes within a tolerable range (Wang *et al*., 2019). WSSV can persist between 15°C and 35°C, with optimal reproduction occurring at 25–28°C, a range that also overlaps with favorable temperatures for shrimp growth. High water temperatures can accelerate WSSV outbreaks, causing nearly complete mortality within 3–10 days at around 33°C. Shrimp exhibit a phenomenon known as "behavioral fever" by moving to warmer areas above 30°C to survive WSSV infections, although this response may reduce viral impact but does not completely eliminate the infection (Rakhshaninejad *et al*., 2023). Conversely, temperatures around 27°C have been reported to accelerate the progression of WSSV infection and increase shrimp mortality (Rahman *et al*., 2007). Therefore, maintaining stable water temperatures are essential for managing WSSV in shrimp farms, as daily temperature fluctuations have been associated with an increased risk of WSSV outbreaks (Millard *et al*., 2021; Xiao *et al*., 2024). Temperature also influences vibriosis in shrimp. Warmer temperatures can promote the growth of *Vibrio* species, including *Vibrio parahaemolyticus* (Vp), a common pathogen. The growth of *Vibrio* spp. generally increases with temperature, although this relationship is complex and can be modulated by other environmental factors. Seasonal temperature changes also affect the prevalence of *Vibrio* species, with higher incidences typically observed during warmer months. The relationship between temperature and Acute Hepatopancreatic Necrosis Disease (AHPND) is less clear; however, the bacteria associated with AHPND, including *V. parahaemolyticus*, are known to be temperature-sensitive. Low temperatures, below -18°C to -24°C, can inactivate these bacteria, thereby reducing their pathogenic potential. In contrast, higher incidences of AHPND have been observed at temperatures of 27–28°C, suggesting that these conditions may enhance the pathogen's infectivity (López-Cervantes *et al*., 2021).

Salinity and disease incidence in shrimp

Shrimp are euryhaline organisms, meaning they can tolerate a wide range of salinity levels. However, each species and life stage has specific salinity preferences. *L. vannamei*, for instance, can survive in salinities between 0.5 to 45 ppt but grows best at 20–25 ppt. Low salinity levels can reduce shrimp growth and immunity (Rahi *et al*., 2021; Supono *et al*., 2022). Salinity fluctuations, especially abrupt changes, can cause osmotic stress, disrupting the shrimp’s internal salt balance. Young shrimp are particularly vulnerable, and genetic factors can influence their tolerance to salinity stress. Prolonged exposure to low or high salinity can lead to dehydration, metabolic disturbances, and weakened immune systems, leaving shrimp more susceptible to disease (Rahi *et al*., 2021). Regularly monitoring and adjusting salinity levels are essential in shrimp farming to prevent mortality and stress. Slowly acclimating shrimp to new salinity levels helps them adapt and survive better. Farmers should watch for signs of salinity stress, such as changes in color, feeding behavior, and physical indicators. Along with salinity, maintaining good water quality, providing proper nutrition, and using biosecurity measures are crucial for supporting shrimp health and resilience to changing environments. Salinity also influences disease outbreaks. Both high and low salinity can increase the risk of diseases like WSSD. For example, infections with *Enterocytozoon hepatopenaei* (EHP) are more severe at higher salinity levels (Aranguren Caro *et al*., 2021). Additionally, low salinity facilitates the spread of infectious myonecrosis virus

(IMNV) (Gazzieno, 2015). Salinity changes can also impact the shrimp's microbiome of gastrointestinal, leading to an increase in opportunistic pathogens like *Vibrio* under low salinity conditions (Chang *et al*., 2024). Maintaining optimal salinity is crucial for shrimp health and disease prevention.

Dissolved oxygen and disease incidence in shrimp

Dissolved oxygen (DO) is crucial for the health and survival of shrimp in aquaculture. Optimal DO levels of 5 ppm or higher are necessary for supporting shrimp growth, immune function, and overall well-being. Low DO levels, or hypoxia, can cause stress in shrimp, making them more vulnerable to diseases by weakening their immune system and increasing oxidative stress (Boyd, 2022). Several factors, including temperature, organic waste, poor water circulation, and high stocking densities, can reduce DO levels in shrimp ponds. Higher temperatures decrease oxygen solubility, while organic matter such as uneaten feed and shrimp waste depletes oxygen during decomposition. Managing waste and ensuring proper aeration and water circulation help maintain adequate oxygen levels (Tho *et al*., 2011; Wiyoto *et al*., 2016). Low DO can negatively impact shrimp health, leading to reduced growth, poor feed efficiency, and heightened disease susceptibility. Conditions of low oxygen also favor the growth of harmful bacteria like *Vibrio parahaemolyticus*, which causes diseases like *Vibriosis*. Additionally, low oxygen levels create a favorable environment for epibiont parasites such as *Zoothamnium* and *Vorticella*, further stressing shrimp (Marista *et al*., 2023). Research shows a strong connection between low DO and higher mortality rates in shrimp infected with WSSV. Hypoxia can impair the shrimp's defense mechanisms, making them more susceptible to infections like WSSV (Lehmann *et al*., 2016). To prevent disease and promote shrimp health, aquaculturists must maintain adequate DO levels by using good pond management practices, such as controlling stocking densities, feeding properly, and employing effective aeration and water circulation systems.

pH and disease incidence

In shrimp farming, maintaining water pH between 7.8 and 8.5 is essential for minimizing stress, promoting growth, and supporting immune responses. Significant pH deviations can weaken shrimp and increase disease susceptibility, emphasizing the need for careful pH regulation. Pond pH is influenced by acid sulfate soils, aluminum contamination, algal activity, microbial populations, and water alkalinity. Low alkalinity often leads to pH instability, while higher alkalinity serves as a buffer, helping maintain a stable pH. Common pond management practices, such as adding lime or dolomite, are used to stabilize water conditions (Komarudin *et al*., 2021).

Fluctuations in pH affect critical physiological processes in shrimp, including osmoregulation, oxygen consumption, and ammonia excretion. High pH stress can disrupt gill function, impair ammonia excretion, and activate immune-related genes, which may lead to metabolic and growth challenges (Mariu *et al*., 2023). While species like *L. vannamei* may adapt to pH stress over time, maintaining stable pH levels is essential to lower the risks of infections such as white spot syndrome virus (WSSV) and acute hepatopancreatic necrosis disease (AHPND) (Millard *et al*., 2021). Appropriate pH management practices, including the addition of $CaCO_3$ to increase pH and molasses to lower it, can prevent disease outbreaks and improve water quality. Pond preparation with hydrated lime is effective in controlling pathogens like WSSV, contributing to healthier shrimp populations (Martins *et al*., 2017). Maintaining a stable pond pH is vital for shrimp health, immune resilience, and disease prevention. Implementing effective pH management strategies helps promote sustainable aquaculture practices, ensuring the well-being of shrimp and supporting aquaculture productivity. Overall, maintaining water pH between 7.8 and 8.5 is essential in shrimp farming for health, growth, and disease resistance, with daily fluctuations ideally remaining under 0.5. Factors such as soil acidity, water alkalinity, algae, and microorganisms affect pond pH, while higher alkalinity provides buffering stability. Proper management techniques, including lime and dolomite applications, can stabilize pH levels, preventing physiological stress that disrupts osmoregulation and ammonia excretion. Stable pH helps reduce the risks of infections like WSSV and AHPND, supporting better growth and immune function. Effective pH control strategies, such as using $CaCO_3$ or molasses, are crucial for preventing disease outbreaks in aquaculture.

Ammonia and nitrite levels and disease incidence

Ammonia and nitrite, toxic byproducts resulting from organic waste and feed remnants, pose significant risks in shrimp aquaculture, leading to gill damage, respiratory stress, and weakened immune defenses. Their toxicity is influenced by environmental factors such as pH, salinity, dissolved oxygen, temperature, and shrimp age, with higher pH, lower salinity, and reduced oxygen levels increasing toxicity. Younger shrimp are particularly susceptible. Low-salinity cultures intensify nitrite toxicity, especially for *L. vannamei*, highlighting the need for careful water quality management (Han *et al*., 2017). Strategies like aeration, controlled feeding, sludge management, and adding beneficial bacteria are essential to reduce ammonia and nitrite levels, improve water quality, and mitigate disease risks, including susceptibility to white spot syndrome virus (WSSV) and acute hepatopancreatic necrosis disease (AHPND) (Hong *et al*., 2016; Xue *et al*., 2017).

Stocking density and disease incidence

High stocking density in shrimp aquaculture leads to elevated stress, competition, and waste accumulation, which weaken the immune system and increase disease risks. Overcrowding contributes to oxidative stress, impairing immune defenses and promoting infections. Research on *L. vannamei* shows that high-density conditions reduce survival rates and elevate stress markers, such as HSP70 expression. To mitigate these effects, strategies including the use of nursery systems, improved nutrition, and advanced pond cleaning technologies can be implemented. Maintaining optimal stocking densities is essential for promoting shrimp health and reducing the likelihood of disease outbreaks in farming operations.

Feeding and disease incidence

Shrimp farming environments present unique stressors, which influence feed consumption and nutritional needs. Factors like shrimp size, pond conditions, algal presence, and stocking density play a role in feeding dynamics and overall nutrition. Despite the importance of efficient feeding, studies show that approximately 40% of feed remains uneaten in ponds, especially when inappropriate use of feeding trays lead to overfeeding or food waste. This excess feed impacts water quality, elevating stress and increasing disease risk. In extensive farming systems, shrimp can rely on natural pond resources, but semi-intensive and intensive systems, with their higher densities, require precise feeding. Feed quality must support shrimp resilience in these crowded conditions. Nutrients such as vitamins C and E, astaxanthin, and unsaturated fatty acids enhance stress tolerance and immune function. Recent research also highlights the benefits of adding nucleotides, which support cellular repair and growth, to shrimp diets (Emerenciano *et al*., 2022).

Overfeeding and underfeeding are key challenges, both of which can compromise shrimp immunity and growth. In semi-intensive systems, feeding trays and other monitoring methods help regulate feed intake, reducing nutrient deficiencies and waste. Proper feeding management, including the selection of appropriate feed types and quantities, is crucial to ensure that shrimp achieve optimal growth and are less prone to disease (Van *et al*., 2017). Shrimp farming requires a balanced approach to nutrition that accounts for the stressors of semi-intensive and intensive systems. High-quality, nutrient-rich feed, alongside effective feeding strategies, plays a pivotal role in supporting shrimp health, minimizing disease risks, and maintaining sustainable water quality in aquaculture. In shrimp farming ponds, algae blooms are largely driven by increased levels of organic matter and nutrients, often resulting from poor pond preparation during the fallow period and inefficient feeding and water management (Boyd, 2003). Overfeeding exceeds the pond’s carrying capacity, leading to increased organic matter and nitrogenous compounds. This promotes bacterial growth, lowers dissolved oxygen levels, and elevates the feed conversion ratio (FCR), reducing shrimp yields. Poor nutritional management causes the daily input of excess nitrogen and phosphorus, which fosters the growth of cyanobacteria. These algae, after rapid growth, die off, leaving behind organic matter, including phytoplankton and zooplankton remains (Mohammed *et al*., 2024) (Fig. 4).

Therefore, nutrition plays a vital role in organic matter production during shrimp culture. For every 100 kg of feed, about 95% is consumed by the shrimp, leaving 5 kg as uneaten food. Of the consumed feed, approximately 67 kg is absorbed, resulting in 28 kg being excreted as waste. In total, the uneaten food and shrimp waste amount to 33 kg, comprising 13 kg of proteins, 14 kg of carbohydrates, 1.9 kg of fats, 0.1 kg of minerals, 0.1 kg of vitamins, and 1.1 kg of fiber and other nutrients (Quintero and Roy, 2010) (Fig. 5).

Figure 4: Poor water quality in shrimp ponds during the rearing phase, exacerbated by elevated nutrient levels resulting from overfeeding.

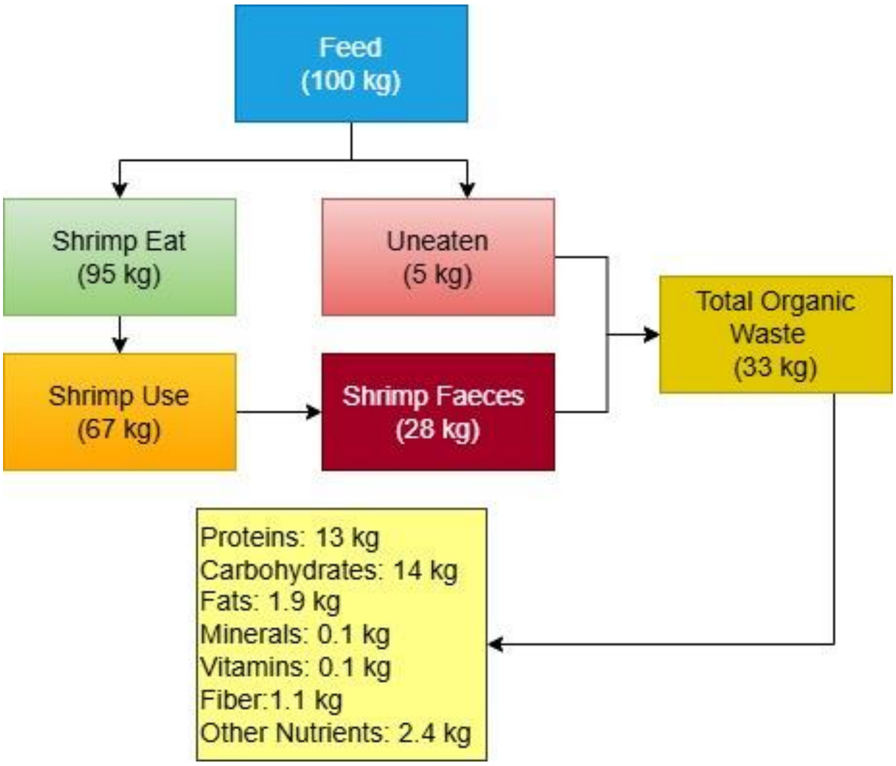

Figure 5: Schematic picture of the amount of food used in the shrimp ponds.

The accumulation of this organic material, combined with shrimp carcasses, uneaten food, and feces, leads to layers of organic waste on the pond bed. Without proper decomposition, this buildup produces the so-called "black soil" and triggers anaerobic fermentation, releasing toxic gases like hydrogen sulfide, ammonia, and methane. These gases create foul odors and are harmful to shrimp health (Susetyaningsih *et al*., 2020) (Fig. 6).

Figure 6: Accumulation of organic matter in shrimp farming pond.

Conclusion

The global shrimp farming industry plays a vital role in meeting seafood demand but continues to face significant challenges in maintaining sustainable production systems. Intensive and semi-intensive farming practices often expose shrimp to multiple environmental and management-related stressors, which can weaken their immune systems and increase susceptibility to diseases. Effective management of feeding practices, water quality, nutrition, and biosecurity are essential for minimizing stress and reducing the risk of disease outbreaks. Regular monitoring and early disease detection, combined with the implementation of best management practices, help maintain shrimp health and improve farm productivity. By adopting advanced technologies and proactive farm management strategies, the industry can enhance sustainability and continue to play a crucial role in supplying high-quality seafood to global markets.

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Conflicts of interest

The authors have declared no conflict of interest.

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