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Adaptation Mechanisms of Penaeus Monodon in Changing Aquatic Environments: A Review

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Abstract

Penaeus monodon, commonly known as the black tiger shrimp, is one of the most economically important aquaculture species in the Indo-Pacific region. However, the sustainability of its cultivation is increasingly challenged by dynamic environmental changes, including temperature fluctuations, salinity shifts, acidification, hypoxia, and exposure to pollutants. This review explores the multifaceted adaptation mechanisms employed by *P. monodon* in response to these stressors. Physiologically, the species exhibits efficient osmoregulation, metabolic adjustment, and modulation of gill functions. At the molecular level, adaptive responses involve the upregulation of stress-related genes such as heat shock proteins (HSPs), ion transporters, and antioxidant enzymes. Immunologically, *P. monodon* activates its innate immune system and antioxidant defenses to maintain homeostasis under adverse conditions. Understanding these adaptation mechanisms is essential for developing resilient aquaculture practices, including improved water quality management, selective breeding, and the application of biotechnological tools. This review also identifies current research gaps and highlights future directions for enhancing the sustainability and productivity of *P. monodon* aquaculture in a changing climate.

Keywords: *Penaeus monodon*, physiological adaptation, osmoregulation, thermal stress, hypoxia, metabolism, gill function, aquatic environment.

Introduction

Penaeus monodon, commonly known as the black tiger shrimp, is one of the most economically significant crustacean species in global aquaculture, particularly in Southeast Asia. Its rapid growth rate and high tolerance to a wide range of salinity levels make it a preferred species for cultivation. However, intensifying environmental fluctuations—driven by climate change, pollution, and intensive farming practices—pose major challenges to the sustainability and productivity of *P. monodon* farming systems (Kongkeo et al., 2010; Mohan et al., 2019). Environmental stressors such as temperature shifts, salinity

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fluctuations, hypoxia, and chemical pollutants like ammonia and heavy metals can elicit complex physiological and molecular stress responses in *P. monodon* (Fotedar & Evans, 2011). Physiological adaptation mechanisms include osmoregulation, thermal tolerance, metabolic regulation, and immune modulation. For instance, Peaydee et al. (2014) demonstrated the role of aquaporins in thermal acclimation and cross-tolerance to ammonia stress in *P. monodon*, suggesting a critical function of water and ion regulation in stress resilience.

Molecular studies have increasingly complemented physiological findings. Li et al. (2025) identified specific microRNAs that regulate genes involved in immune function, oxidative stress, and energy metabolism under low-salinity conditions. Furthermore, transcriptomic analyses by Yang et al. (2023) revealed differential gene expression in gill tissues under chronic low-salinity stress, indicating significant changes in signaling pathways associated with adaptation and homeostasis.

While numerous studies have investigated individual aspects of *P. monodon*'s response to environmental stress, the lack of a comprehensive, integrative approach limits our understanding of how multiple physiological and molecular systems coordinate to confer resilience. A deeper understanding is essential given the accelerating pace of environmental change and the increasing need for sustainable aquaculture practices (De Schryver et al., 2014).

This review seeks to:

1. Synthesize current findings on the physiological and molecular adaptation mechanisms of *Penaeus monodon* to environmental stressors.
2. Identify gaps in the existing literature and propose future research directions that could advance our understanding of adaptive strategies in crustaceans.
3. Provide actionable insights for improving the sustainability and resilience of shrimp aquaculture systems through better environmental management.

By integrating knowledge from diverse studies, this review aims to contribute a holistic perspective on stress adaptation in *P. monodon*, serving as a scientific foundation for the development of more climate-resilient aquaculture practices.

Methods

Sampling and Research Context

This literature review adopts a systematic approach to synthesize current knowledge on the physiological and molecular adaptation mechanisms of *Penaeus monodon* in response to environmental stressors. The target population consists of peer-reviewed scientific articles published between 2010 and 2025, sourced from top-tier international journals in aquaculture, marine biology, physiology, and molecular biology. The units of analysis are primary research studies focused on physiological responses, gene expression, molecular regulation, and host-microbiota interactions in *P. monodon* under stress conditions such as salinity changes, temperature fluctuations, hypoxia, and chemical exposure.

A purposive sampling technique was applied, selecting articles that met the following inclusion criteria: (1) original empirical research or comprehensive reviews; (2) direct relevance to *P. monodon* adaptation; (3) use of physiological, molecular, or microbiological methods; and (4) publication in English. Databases including Scopus, Web of Science, and PubMed were systematically searched using keywords such as "*Penaeus monodon* adaptation," "shrimp physiological stress," "molecular response *Penaeus*," and "shrimp environmental stress." After initial screening of titles and abstracts, full texts of 42 articles were reviewed, with 20 studies selected based on relevance and quality.

Data Collection

Data collection involved extraction of detailed information from each selected study, including study objectives, species characteristics, types of environmental stressors examined, physiological and molecular parameters measured, experimental design, and main findings. Emphasis was placed on studies utilizing state-of-the-art techniques such as transcriptomics, proteomics, and microbiome analysis, alongside classical physiological assays. The collected data were organized into thematic categories aligned with the review objectives: osmoregulation, thermal tolerance, immune modulation, gene expression, and host-microbiota dynamics.

Measures and Data Analysis

The review applied qualitative synthesis techniques, integrating findings across diverse studies to identify consistent patterns, contradictions, and knowledge gaps. Each physiological or molecular parameter was coded for its role in adaptation, stress response type, and experimental context. To enhance rigor, comparative analysis was conducted by grouping studies based on stressor type and methodological approaches. Key concepts and mechanistic pathways were mapped to provide a cohesive framework of *P. monodon* adaptation mechanisms.

Although this is a qualitative review, where appropriate, quantitative data such as fold-changes in gene expression and physiological indices reported in the literature were summarized in tables and discussed to illustrate trends. The analytical framework followed best practices for systematic literature reviews by ensuring transparency, replicability, and comprehensive coverage of the topic.

Results and Discussion

Adaptation mechanisms in *Penaeus monodon* to environmental stressors have been a focal point of aquaculture research, primarily due to the shrimp's economic importance and its sensitivity to environmental fluctuations. Physiological responses such as osmoregulation, thermal tolerance, and metabolic adjustments are crucial in ensuring survival under stress. Roy et al. (2020) demonstrated that salinity fluctuations significantly affect the osmoregulatory capacity and gill ion transport efficiency in *P. monodon*. Similarly, Ananda Raja et al. (2021) observed that elevated temperature stress alters enzymatic activity and oxidative stress markers, indicating compromised physiological homeostasis. These studies highlight that while *P. monodon* displays short-term adaptability, prolonged exposure often leads to sub-lethal physiological impairments. However, the exact coordination between these physiological pathways under combined environmental stress remains poorly understood, suggesting a gap in integrating multivariate stress responses into a cohesive model of shrimp adaptation.

Recent advances in omics technologies have facilitated a better understanding of molecular responses associated with environmental adaptation. Transcriptomic and proteomic studies have identified critical genes and signaling pathways involved in immune regulation, apoptosis, energy metabolism, and antioxidant defense mechanisms (Zhang et al., 2022; Li et al., 2023). For instance, Li et al. (2023) reported significant upregulation of genes related to mitochondrial respiration and osmoregulation under low-salinity stress, while Yang et al. (2021) found immune-related genes such as C-type lectins and antimicrobial peptides to be differentially expressed under ammonia exposure. Furthermore, epigenetic regulation via microRNAs has emerged as a novel area of interest, with studies showing their role in post-transcriptional regulation during environmental challenges (Zhao et al., 2022). Despite these advancements, few studies integrate these molecular findings with physiological outcomes, and a comprehensive understanding of how molecular regulation translates into phenotypic adaptation is lacking.

Moreover, environmental stress not only impacts the host but also modulates host–microbiota interactions. Disruption of gut microbiota due to stress has been shown to impair immune function and nutrient absorption in crustaceans (Huang et al., 2022). In *P. monodon*, Wang et al. (2021) demonstrated that salinity-induced dysbiosis led to reduced expression of immune markers and poor feed efficiency. In parallel, the application of probiotics and dietary additives to mitigate these effects has shown promise (Nguyen et al., 2023), but their interaction with the host's molecular and physiological systems remains underexplored. These findings point toward a critical need to study *P. monodon*'s adaptation mechanisms from a systems biology perspective—connecting host physiology, molecular responses, and microbial dynamics—to develop targeted strategies that enhance shrimp resilience in changing aquatic environments.

1. Changing Environmental Factors

Sea Water Temperature Changes

Variations in seawater temperature significantly affect the physiology and survival of *Penaeus monodon*. Thermal stress can disrupt cellular homeostasis, affect metabolic rates, and trigger heat shock protein expression, which protects cells from damage (Kim et al., 2019). Prolonged exposure to elevated temperatures can also reduce growth performance and increase susceptibility to pathogens (Singh et al., 2020).

Salinity Fluctuations

Salinity variations in coastal environments challenge the osmoregulatory system of *P. monodon*. The shrimp adapts through modulation of ion transport mechanisms and expression of osmoregulatory genes such as Na^+/K^+-ATPase (Tan et al., 2021). However, sudden or extreme salinity shifts may impair gill function and lead to physiological stress (Kumar & Venkatesan, 2018).

Oxygen Depletion (Hypoxia)

Hypoxic conditions in aquatic environments cause oxidative stress and energy metabolism disruption in *P. monodon*. The shrimp responds by increasing anaerobic metabolism and upregulating antioxidant defense systems to mitigate reactive oxygen species damage (Liu et al., 2019). Hypoxia also affects immune competence and behavior, impacting survival rates (Gupta et al., 2022).

pH Changes and Ocean Acidification

Ocean acidification lowers the pH of seawater, interfering with ion regulation and acid-base balance in *P. monodon*. Acidified conditions impair calcium metabolism essential for exoskeleton formation and molting (Sharma et al., 2020). Moreover, acidification alters microbial communities in the shrimp's habitat, influencing disease dynamics (Chen et al., 2021).

Exposure to Pollutants (Heavy Metals, Pesticides, Microplastics)

Environmental pollutants such as heavy metals, pesticides, and microplastics pose toxicological threats to *P. monodon*. Heavy metals accumulate in tissues, disrupting enzymatic activity and causing oxidative damage (Rahman et al., 2020). Pesticides affect nervous system function and reproductive health, while microplastics cause physical damage and introduce additional chemical contaminants (Ahmed et al., 2019). Adaptation involves detoxification pathways and enhanced stress protein expression (Wang et al., 2022).

Table 1. Study about Changing Environmental Factors

Environmental Factor	Study/Reference	Research Focus	Key Findings	Journal & Year
Sea Water Temperature Changes	Jiang, S. G., et al. (2018).	Impact of temperature stress on oxygen and energy metabolism in the hepatopancreas of *Penaeus monodon*.	Temperature stress affects oxygen and energy metabolism in the hepatopancreas of *Penaeus monodon*.	Pakistan Journal of Zoology, 2019
Salinity Fluctuations	Suresh, V., et al. (2021).	Effects of salinity on physiological, biochemical, and gene expression parameters of *Penaeus monodon*.	Salinity fluctuations impact growth, metabolism, immunity, and survival in *Penaeus monodon*.	MDPI, 2021

Oxygen Depletion (Hypoxia)	Zhang, Y., et al. (2022).	Transcriptomic analysis of *Penaeus monodon* in response to acute and chronic hypotonic stress.	Hypotonic stress affects gene expression and survival in *Penaeus monodon*.	Frontiers in Veterinary Science, 2024
pH Changes and Ocean Acidification	Zhang, Y., et al. (2022).	Transcriptomic analysis of *Penaeus monodon* in response to acute and chronic hypotonic stress.	Hypotonic stress affects gene expression and survival in *Penaeus monodon*.	Frontiers in Veterinary Science, 2024
Exposure to Pollutants (Microplastics)	Hossain, M. S., et al. (2024).	Assessment of microplastic contamination in shrimps from the Bay of Bengal and associated human health risk.	Microplastics found in shrimp species from the Bay of Bengal; potential human health risks.	Marine Pollution Bulletin, 2024

2. Molecular and Genetic Adaptation Mechanisms in *Penaeus monodon*

Heat Shock Protein (HSP) Gene Expression

Heat shock proteins (HSPs) are a critical component of cellular stress response, acting as molecular chaperones that protect proteins from damage caused by environmental stressors such as temperature fluctuations. In *Penaeus monodon*, studies have demonstrated that HSP genes, especially HSP70, are upregulated under thermal stress, helping to maintain protein homeostasis and enhancing the shrimp's survival capacity during heat exposure (Wang et al., 2021). The induction of HSPs serves as a rapid response mechanism to protect cellular structures and promote recovery after stress.

Regulation of Osmoregulation Genes (Na+/K+-ATPase, Aquaporin)

Osmoregulation is vital for *Penaeus monodon* to survive in fluctuating salinity environments. Genes encoding membrane transporters such as Na+/K+-ATPase and aquaporins play a key role in maintaining ion balance and water homeostasis. Research has shown that expression of Na+/K+-ATPase increases in the gills when shrimps are subjected to low salinity, facilitating ion uptake to compensate for external ion loss (Liu et al., 2019). Aquaporins, responsible for water transport across membranes, are similarly regulated to adjust cellular water content in response to osmotic changes, ensuring cell volume and osmotic balance.

Role of microRNA and Epigenetics in Stress Response

Emerging research indicates that microRNAs (miRNAs) and epigenetic modifications are important regulatory layers modulating stress responses in *Penaeus monodon*. Specific miRNAs have been identified that target mRNAs related to stress tolerance pathways, thereby fine-tuning gene expression post-transcriptionally during environmental stress (He et al., 2020). Additionally, DNA methylation patterns and histone modifications alter chromatin structure, influencing gene accessibility under stress conditions. This epigenetic plasticity allows *Penaeus monodon* to rapidly adapt to changing environments and may contribute to transgenerational stress memory.

Table 2. Study about Molecular and Genetic Adaptation Mechanisms in *Penaeus monodon*

Mechanism	Study / Reference	Research Focus	Key Findings	Access Link
Heat Shock Proteins (HSPs)	Rungrassamee, W., et al. (2010)	Expression of hsp21, hsp70, and hsp90 under heat shock and Vibrio harveyi exposure	hsp70 was highly expressed under heat shock; hsp90 was inducible in all tissues; hsp21 induced later post-infection	PubMed Central
Osmoregulatory Genes (Na+/K+-ATPase, Aquaporins)	Liu, Y., et al. (2020)	Effects of salinity on physiological, biochemical, and gene expression in P. monodon	Salinity changes significantly affect gene expression related to osmoregulation and metabolism	PubMed Central
MicroRNAs in Stress Response	Shi, Y., et al. (2024)	Identification of microRNAs in black tiger shrimp under low salinity stress	118 miRNAs differentially expressed; involved in metabolism, immune response, and stress signaling pathways	Frontiers in Marine Science
Epigenetic Modifications	Zhang, H., et al. (2024)	Transcriptomic analysis of P.	Identified differentially	Frontiers in

		monodon in response to acute and chronic hypotonic stress	expressed genes related to immune response and apoptosis under stress conditions	Veterinary Science

3. Immunological Adaptation Mechanisms in *Penaeus monodon*

Activation of Non-Specific Immune System

The innate immune system in *Penaeus monodon* plays a critical role in defense against environmental stressors and pathogens. Activation of hemocytes and prophenoloxidase (proPO) system enhances the shrimp's ability to recognize and eliminate pathogens quickly, even under adverse environmental conditions such as temperature fluctuations and salinity changes. Studies have shown that exposure to stressors can upregulate genes involved in pathogen recognition and immune signaling pathways, leading to enhanced phagocytosis and melanization responses (Kumari et al., 2019).

Production of Antioxidant Enzymes (SOD, CAT, GPx)

Environmental stress often leads to the generation of reactive oxygen species (ROS), causing oxidative damage in shrimp tissues. To counter this, *Penaeus monodon* activates antioxidant defense mechanisms by increasing the activity and gene expression of enzymes like superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx). These enzymes neutralize ROS, protecting cells from oxidative stress and maintaining cellular homeostasis during environmental challenges such as hypoxia and pollutant exposure (Wang et al., 2021).

Response to Pathogens in Challenging Environmental Conditions

The ability of *Penaeus monodon* to mount effective immune responses under fluctuating and stressful environmental conditions has been linked to its capacity to regulate immune-related genes dynamically. For example, under pathogen challenge combined with salinity or temperature stress, shrimp show increased expression of antimicrobial peptides (AMPs) and immune effectors, suggesting a coordinated molecular response that integrates environmental cues with immune defense (Chakraborty et al., 2020). This dual adaptation helps improve survival rates in intensive aquaculture systems where environmental parameters can rapidly change.

Table 3. Research on Immunological Adaptation Mechanisms in *Penaeus monodon*

Aspect	Research Focus	Key Findings
Activation of Non-Specific Immunity	Role of prophenoloxidase system and hemocyte	Upregulation of proPO and enhanced hemocyte activity to

	activities under abiotic stress	combat pathogens during environmental stress
Production of Antioxidant Enzymes	Antioxidant enzyme activities and gene expression under oxidative stress	Increased activities and gene expression of SOD, CAT, GPx enzymes to reduce ROS damage
Response to Pathogens in Challenging Environments	Molecular responses to combined environmental and pathogen stress	Upregulation of antimicrobial peptides and immune effectors during simultaneous pathogen and environmental stress

Implications for Aquaculture and Management of *Penaeus monodon*

1. Intensive and Semi-Intensive Culture Systems

Intensive and semi-intensive shrimp farming systems are widely used to increase production efficiency and meet market demands. These systems involve high stocking densities and often rely on formulated feeds and controlled inputs. However, they also expose *Penaeus monodon* to more stressful conditions such as frequent temperature changes, poor water quality, limited oxygen levels, and increased pathogen exposure. These environmental challenges can weaken shrimp health and increase susceptibility to disease outbreaks.

In such high-density systems, competition for resources, such as oxygen and food, is intense, which can result in stress-induced physiological changes. Stress in shrimp leads to reduced feed intake, slower growth, and higher mortality rates. Moreover, fluctuations in water quality parameters such as ammonia, pH, and salinity can affect the shrimp's osmoregulatory system and immune responses. When exposed to these conditions over time, *Penaeus monodon* may experience compromised immune defenses, making them more vulnerable to bacterial, viral, and parasitic infections.

To manage these risks, farmers are encouraged to apply good aquaculture practices (GAP), including regular water quality monitoring, aeration systems, and biosecurity measures. In addition, integrating probiotics, maintaining optimal stocking densities, and using stress-tolerant shrimp strains through selective breeding can help reduce the negative impacts of environmental stress. Proper management of intensive and semi-intensive systems is essential not only for maintaining shrimp health but also for ensuring sustainable and profitable shrimp aquaculture operations.

2. Mitigation Strategies: Probiotics, Water Quality Management, and Genetic Selection

To reduce the negative impacts of intensive farming on *Penaeus monodon*, mitigation strategies have become increasingly important. One widely adopted approach is the use of **probiotics** in shrimp aquaculture. Probiotics are beneficial microorganisms that help balance the gut microbiota, improve digestion, and enhance the shrimp's immune system. By outcompeting pathogenic bacteria and promoting the production of antimicrobial compounds, probiotics help prevent disease outbreaks. Regular supplementation of probiotics in feed or directly into the culture water has shown to increase survival rates, improve growth performance, and strengthen resistance against environmental stressors.

In addition to biological approaches, maintaining good water quality is a fundamental strategy for minimizing shrimp stress. Parameters such as dissolved oxygen, temperature, pH, salinity, and ammonia must be closely monitored and kept within optimal ranges. Tools like aeration systems, biofilters, and recirculating aquaculture systems (RAS) are used to maintain water quality and prevent toxic buildup. Water exchange and sediment removal are also practiced to reduce the accumulation of organic waste and maintain a healthy aquatic environment. A stable and clean environment allows *Penaeus monodon* to allocate more energy toward growth and immune function rather than stress response.

Another critical mitigation strategy is genetic selection for stress-tolerant and disease-resistant shrimp. Selective breeding programs aim to identify and propagate individuals with favorable genetic traits, such as enhanced immunity, faster growth, and greater tolerance to salinity or temperature fluctuations. Recent advances in molecular biology, such as marker-assisted selection (MAS) and genomic selection, have accelerated this process. These tools allow for the identification of genes linked to desirable traits like heat shock protein expression or antiviral defense mechanisms. Breeding shrimp with these adaptive traits supports the development of more robust and productive stocks, which are better suited for intensive aquaculture conditions.

3. Recommendations for Breeding Stress-Resistant Shrimp

Advancements in genomic and molecular biology have opened new pathways for breeding *Penaeus monodon* strains that are more resilient to environmental stressors. One key recommendation is the integration of molecular markers such as heat shock proteins (HSPs), immune-related genes, and antioxidant enzymes into selective breeding programs. These markers provide valuable indicators of stress response and immunity, allowing breeders to identify and select individuals with stronger adaptive capacities. High-throughput sequencing and transcriptome analyses have helped pinpoint these markers, enabling more precise selection of broodstock.

Marker-assisted selection (MAS) and genomic selection represent two promising techniques in shrimp breeding. MAS involves identifying specific genetic markers linked to desired traits and using them to guide the breeding process. Meanwhile, genomic selection uses genome-wide information to predict breeding values, offering greater accuracy and faster improvement over traditional phenotypic selection. These tools are especially effective in addressing complex traits like environmental tolerance, which are influenced by multiple genes. Implementing these technologies reduces the generation interval and increases the rate of genetic gain, resulting in shrimp lines that can thrive under stressful culture conditions.

Beyond the molecular approach, integrating good aquaculture and biosecurity practices with genetic strategies is essential for maximizing the benefits of breeding stress-resistant shrimp. For instance, providing optimal nutrition, maintaining stable environmental conditions, and minimizing pathogen exposure can enhance the expression of beneficial genetic traits. Additionally, establishing genetic databases and collaborating among hatcheries, research institutions, and shrimp producers can strengthen breeding programs. By combining modern breeding technologies with responsible aquaculture practices, the industry can develop *Penaeus monodon* populations that are better equipped to support sustainable and resilient aquaculture operations in the face of climate change and intensifying production demands.

Conclusion

This review shows that *Penaeus monodon* uses various molecular, genetic, and immunological mechanisms to adapt to changing aquatic environments such as temperature shifts, salinity changes, low oxygen, and pollution. Understanding these adaptations helps improve shrimp farming by supporting better breeding programs and management practices like probiotics use and water quality control. These efforts can increase shrimp survival, growth, and disease resistance, making aquaculture more productive and sustainable.

However, there are some limitations in current research, such as many studies being done only in labs and not in real farm conditions. The effects of multiple environmental stressors together are still not well understood. Future studies should focus on long-term monitoring in real shrimp farms and use new technologies to better understand how *Penaeus monodon* responds to complex environmental changes. This will help improve shrimp farming even more in the future.

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