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# Health Management Techniques for Swimming Crab Under High-Temperature Conditions

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**Abstract** Against the backdrop of global climate change, the frequent occurrence of marine heatwaves significantly impacts the stability and health of swimming crab (*Portunus trituberculatus*) aquaculture systems; indeed, high-temperature stress has become a critical environmental factor constraining the industry's sustainable development. This paper systematically reviews the mechanisms by which high-temperature environments affect the physicochemical properties of culture water, production performance, and disease incidence, focusing on key physiological responses such as metabolic disorders, heightened oxidative stress, compromised immune function, and intestinal microbial imbalance. Based on this, and addressing the health management needs of swimming crabs under high-temperature conditions, the paper summarizes key technical systems, including water quality regulation and ecological optimization, nutritional and immunological enhancement, and intelligent monitoring with precision control. Furthermore, drawing on case studies from typical high-temperature culture seasons, the paper comprehensively evaluates the effectiveness of these health management measures in improving survival rates, mitigating disease risks, and stabilizing production performance. Research indicates that establishing an integrated health management system—grounded in environmental regulation, centered on nutritional and immunological modulation, and supported by digital monitoring—is an effective strategy for enhancing the heat tolerance and aquaculture resilience of swimming crabs. Future efforts should focus on further elucidating the mechanisms of high-temperature stress, developing precision health management technologies, and integrating intelligent aquaculture systems to drive high-quality, sustainable development of the swimming crab industry amidst climate change.

**Keywords** Swimming crab (*Portunus trituberculatus*); High-temperature stress; Health management; Climate change; Intelligent aquaculture

## 1 Introduction

Swimming crab aquaculture, particularly for *Portunus trituberculatus*, has become an important component of coastal aquaculture in East Asia and a high-value segment of the broader crab industry. Farming of *P. trituberculatus* expanded rapidly in east China over the past decade, demonstrating its strong production momentum and growing commercial relevance. At the same time, the global commercial exploitation of swimming crabs has increased markedly, and crab production from fisheries plus aquaculture reached nearly 1.3 million tons in 2015, indicating the substantial scale of the sector. The economic value of swimming crab is further enhanced by premium product forms such as soft-shell crab, which can command high unit prices in retail and restaurant markets, reflecting strong consumer demand and favorable market returns. However, the industrial chain still faces structural constraints, especially because commercial crab culture technology remains relatively incipient and is currently limited to a small number of species and production systems. For *P. trituberculatus* specifically, hatchery seed production still depends heavily on wild-caught broodstock, which creates a potential bottleneck for long-term industry sustainability and increases vulnerability in the supply chain.

High-temperature environments have become one of the most serious ecological and production challenges facing crustacean aquaculture under ongoing climate change. Rising water temperature directly affects the physiology, growth, and survival of aquatic animals, and crustaceans are especially vulnerable because their thermal tolerance is bounded by narrow physiological thresholds (Wang et al., 2025). Reviews of climate change effects on crustacean culture show that elevated temperature can disrupt food intake, moulting, immune response, survival, and broader ecosystem stability, while also increasing the likelihood of disease outbreaks (Daunde et al., 2025). More generally across aquaculture species, temperatures above thermal thresholds tend to reduce performance, health, and productivity, showing that heat stress is not only an environmental issue but also a direct production constraint (Mugwanya et al., 2022). In crustaceans, prolonged thermal stress also forces trade-offs between survival, growth, and reproduction, meaning that even animals capable of short-term acclimation may still suffer reduced farming performance under sustained warming. These patterns make high-temperature episodes, including marine heat waves and seasonal extremes, a central risk factor for the stability and profitability of crustacean farming systems.

Evidence from physiological and immunological studies further shows that heat stress can undermine crustacean health well before visible mortality occurs, which is particularly important for intensive farming. In decapod crustaceans exposed to simulated heat waves, thermal stress increased protective chaperones, antioxidant biomarkers, and integrated stress indices, indicating poorer health status even when mortality did not immediately rise. In Chinese mitten crab, exposure to 32°C altered haemolymph metabolism, suppressed total antioxidant capacity during later stages of stress, and shifted the intestinal microbiota toward lower abundance of beneficial bacteria and higher abundance of pathogenic taxa (Li et al., 2022). In *P. trituberculatus*, rapid temperature stress significantly altered serum non-specific immune factors, including hemocyanin and multiple antioxidant and hydrolase enzymes, showing that acute temperature increase can cause metabolic maladjustment and profound changes in physiological and immune function. More broadly in shellfish, chronic stress combined with microbial or abiotic pressures increases infectious disease risk and reduces recovery capacity, reinforcing the view that thermal stress acts through a stress-immunity axis rather than through temperature alone (Coates and Söderhäll, 2020).

Against this background, research on health management techniques for swimming crab under high-temperature conditions is both scientifically necessary and practically urgent. Because heat stress affects metabolism, immunity, microbial balance, and survival-related trade-offs, effective management must move beyond simple temperature observation and instead target resilience mechanisms at the organism and farm levels (Wang et al., 2025). Recent reviews indicate that adaptation options for crustacean aquaculture include nutritional regulation, selective breeding, biotechnology, and husbandry optimization, all of which are relevant for developing high-temperature health management programs in swimming crab culture (Mugwanya et al., 2022; Daunde et al., 2025). Cellular stress proteins are also increasingly recognized as useful tools in crustacean health management, because heat shock proteins maintain protein homeostasis under stress and appear to enhance disease resistance and protective immunity when properly induced (Kumar et al., 2022). In addition, work on *P. trituberculatus* broodstock suggests that culture performance can be improved through nutritional optimization, supporting the broader idea that targeted physiological management is feasible in this species. Therefore, studying health management techniques for swimming crab under high-temperature conditions is essential for reducing thermal injury, stabilizing production, and supporting the sustainable development of the swimming crab farming industry in a warming climate (Daunde et al., 2025).

## 2 Effects of High Temperature on Swimming Crab Farming Systems

### 2.1 Impact of high temperature on the culture water environment

High temperature alters the physical and chemical stability of culture water, with the strongest effects appearing in dissolved oxygen dynamics and nitrogen metabolism. In crab ponds, dissolved oxygen fluctuates markedly over a 24 h cycle, and bottom waters are more prone to hypoxia because vertical diffusion weakens with depth (Yin et al., 2021). At the same time, higher temperature increases oxygen consumption and ammonia excretion in crabs, which raises the metabolic burden placed on the pond environment and accelerates deterioration of water quality under intensive culture (Liu et al., 2022).

High temperature also interacts with existing pond management constraints, making environmental instability more difficult to control in commercial systems. Survey data from pond aquaculture show that pH commonly remains within a moderate range, whereas ammonia can exceed the national standard across culture systems, indicating that nitrogen accumulation is already a chronic pressure before heat stress is added. Broader aquaculture evidence further shows that continuous monitoring of temperature, pH, dissolved oxygen, and ammonia improves growth and reduces mortality by enabling rapid detection of abnormal water-quality events, which is particularly relevant during summer heat periods (Zein et al., 2023; Flores-Iwasaki et al., 2025).

### 2.2 Impact of high temperature on farming production performance

High temperature can accelerate some developmental processes in swimming crab, but this does not translate into uniformly better production outcomes. In off-season breeding, embryonic development became faster as temperature increased, with total development time shortening from 9.43 d at 27°C to 6.88 d at 33°C; however, development at 31°C became asynchronous and embryo mortality increased, showing that excessive warming trades faster development for poorer developmental quality (He et al., 2022). A similar pattern appears during larval culture: development from zoea to megalopa was fastest at 31°C, but survival declined progressively with increasing temperature, and megalopa survival at 33°C dropped to only 2% (Wu et al., 2024).

For juveniles and crablets, production performance generally follows a unimodal temperature response, with moderate warmth supporting growth and thermal excess suppressing feeding efficiency and survival. In juvenile mud crabs, specific growth rate was optimized around 28.5°C-29.7°C, whereas 35°C reduced survival, feed intake, and feed conversion efficiency and increased oxidative stress (Liu et al., 2022). The same tendency has now been reported for *P. trituberculatus* crablets, in which 30°C produced the highest growth, while 34°C reduced ecdysis frequency, slowed growth, and lowered food intake (Macario et al., 2025).

### 2.3 Farming risks and mortality events induced by high temperature

High temperature raises farming risk not only through direct thermal injury but also by amplifying energetic disturbance during routine culture operations such as handling, grading, and transport. In *P. trituberculatus*, high temperature increased lactate, ADP, AMP, and the ratios ADP/ATP and AMP/ATP, while decreasing ATP and adenylate energy charge, indicating a mismatch between energy demand and supply under thermal stress. When crabs were exposed to air, mortality increased with higher air temperature and longer emersion time, confirming that hot-weather handling can convert routine operational stress into acute survival loss (Lu et al., 2020).

Heat-related farming risk also includes biological losses that emerge when stressed crabs become less resilient to environmental and pathological challenges. Natural farm mortality events in swimming crab have been linked to Decapod iridescent virus 1, with diseased crabs showing slow movement, anorexia, and very high viral loads in gill tissue, illustrating how severe losses can occur once health status collapses in culture populations (Qiu et al., 2023). In parallel, recent crab-behavior synthesis indicates that temperature, dissolved oxygen, ammonia, pH, conspecific interactions, and pathogens jointly shape feeding, sheltering, aggression, and cannibalism, so high-temperature episodes are likely to increase mortality risk through both physiological stress and behavior-mediated system instability (Zhu et al., 2025).

## 3 Physiological Responses of Swimming Crab to Heat Stress

### 3.1 Metabolic regulation

High temperature disrupts metabolic homeostasis in *Portunus trituberculatus* by increasing maintenance energy demand and shifting energy use toward short-term survival rather than growth or storage. Under thermal variation, swimming crabs show increased lactate, elevated ADP/ATP and AMP/ATP ratios, and reduced ATP and adenylate energy charge, indicating a mismatch between energy demand and aerobic supply at high temperature. A similar pattern appears behaviorally, because crabs held at warmer temperatures exhibit higher hemolymph glucose and lactate concentrations together with more intense agonistic activity, showing that heat exposure is coupled to accelerated substrate mobilization and greater energetic expenditure (Su et al., 2020).

Heat stress also appears to reallocate energy among metabolic pathways and physiological functions. Multi-omics evidence indicates that elevated temperature activates lipid and amino acid metabolism at moderate warming and then strengthens glycolysis, gluconeogenesis, and neural-related pathways at higher temperature, supporting rapid energy provision for stress-related behavior (He et al., 2025). Evidence from other stress models in the same species further suggests that when aerobic metabolism becomes constrained, glycogen and lipids are mobilized, fatty acid and amino acid catabolism increase, and anaerobic metabolism becomes more prominent, which is consistent with the metabolic compensation expected under severe heat load (Jiang et al., 2024).

### 3.2 Oxidative stress and immune function responses

High temperature induces oxidative stress in swimming crab, and the initial physiological response is the activation of antioxidant and non-specific immune defenses. In embryos, increasing temperature caused superoxide dismutase, glutathione peroxidase, total antioxidant capacity, and malondialdehyde to rise first and then fall, with the strongest antioxidant response occurring at 31°C, indicating that protective systems are activated before being impaired at more severe temperatures (He et al., 2022). In adults exposed acutely to 34°C, hemocyanin, POD, CAT, and ACP increased transiently, whereas SOD and AKP declined early, showing that rapid warming can quickly disturb free-radical balance and alter immune enzyme activity.

When heat stress is prolonged or intensified, protective capacity appears to become insufficient, increasing the risk of cellular injury and immune dysfunction. Although direct long-term heat studies in swimming crab remain limited, work on this species under other environmental stressors shows a common trajectory in which antioxidant defense, heat shock response, and other cellular stress pathways are activated initially but can later be overwhelmed, leading to oxidative damage and apoptosis (Jiang et al., 2024). Related crab studies under heat stress support this interpretation: in Chinese mitten crab, ACP and AKP increased during early exposure but fell below control levels later, while total antioxidant capacity declined after 48 h, suggesting that sustained high temperature can convert an adaptive response into physiological exhaustion (Li et al., 2022).

### 3.3 Gut health and microbial communities

High temperature likely impairs gut health in swimming crab by weakening digestive performance, disturbing barrier function, and altering microbial community structure. In swimming crab embryos and newly hatched larvae, temperatures above 31°C reduced hatching success and were associated with depressed digestive enzyme activities, especially trypsin and cellulase at 33°C, suggesting that excessive warming compromises later digestive capacity and early-life intestinal function (He et al., 2022). Complementary evidence from ocean acidification experiments in *P. trituberculatus* shows that changes in gut bacteria were closely linked with digestion, stress response, immunity, metabolism, survival, and growth, indicating that gut microbial balance is a central component of physiological resilience in this species (Lin et al., 2020).

Evidence from crab heat-stress models further suggests that thermal stress drives intestinal dysbiosis toward a less favorable microbial profile. In Chinese mitten crab, acute heat stress altered intestinal microbial composition, decreasing beneficial taxa such as *Candidatus*, *Hepatoplasma*, and *Marinifilum* while increasing potentially pathogenic bacteria including *Rhodococcus* and *Morganella* (Li et al., 2022). In swimming crab, dietary lauric acid improved peritrophic membrane thickness, upregulated barrier-related factors, increased beneficial taxa such as *Actinobacteria* and *Rhodobacteraceae*, and reduced Vibrio, which indirectly supports the view that maintaining intestinal structure and microbiota stability is an important route for mitigating heat-associated physiological damage (Zhan et al., 2024).

## 4 Major Health Problems and Disease Risks Under High Temperature

### 4.1 High-temperature-related stress syndromes

High temperature is a primary environmental stressor for *Portunus trituberculatus* because, as a poikilothermic crustacean, its survival and growth are tightly constrained by water temperature (Qian et al., 2024). Acute heat exposure rapidly disturbs physiological homeostasis, causing metabolic maladjustment of free radicals and marked changes in non-specific immune indices such as hemocyanin, SOD, POD, CAT, ACP, and AKP activities.

At the mechanistic level, thermal stress in swimming crab is not only a passive injury process but also a regulated sensory and cellular response. Temperature-responsive TRP channels are broadly activated under temperature challenge, indicating that crabs possess a molecular system for detecting abrupt thermal fluctuations (Qian et al., 2024). In parallel, Hsp70 in *P. trituberculatus* functions as an inducible stress-related molecule linked to innate immune defense, supporting the view that heat stress can shift the animal into a protective but energetically costly stress-response state.

### 4.2 Risks of bacterial diseases and opportunistic infections

High temperature can increase bacterial disease risk in crab culture not simply by favoring a single pathogen, but by simultaneously weakening host defenses and changing the surrounding microbial environment. In aquaculture systems more broadly, elevated water temperatures reduce immunocompetency and increase disease susceptibility, while also increasing loads of opportunistic *Vibrionaceae* in the water column (Samsing and Barnes, 2024). This pattern is relevant to swimming crab because *Vibrio alginolyticus* is already recognized as a major causative agent of emulsification disease associated with large mortality in *P. trituberculatus*.

The infection hazard is amplified during periods when host barriers or physiological stability are compromised. During molting and immediately after molting, swimming crabs are especially vulnerable because the hard carapace and cuticle, which normally act as the first physical barrier against pathogen invasion, are temporarily weakened (Liu et al., 2022). More generally, opportunistic bacterial disease in aquaculture is increasingly understood as a multicausal process driven by environmental stress, host damage, and microbial shifts rather than a simple one-pathogen-one-disease model, which makes high-temperature episodes particularly dangerous under intensive farming conditions (Samsing and Barnes, 2024) (Figure 1).

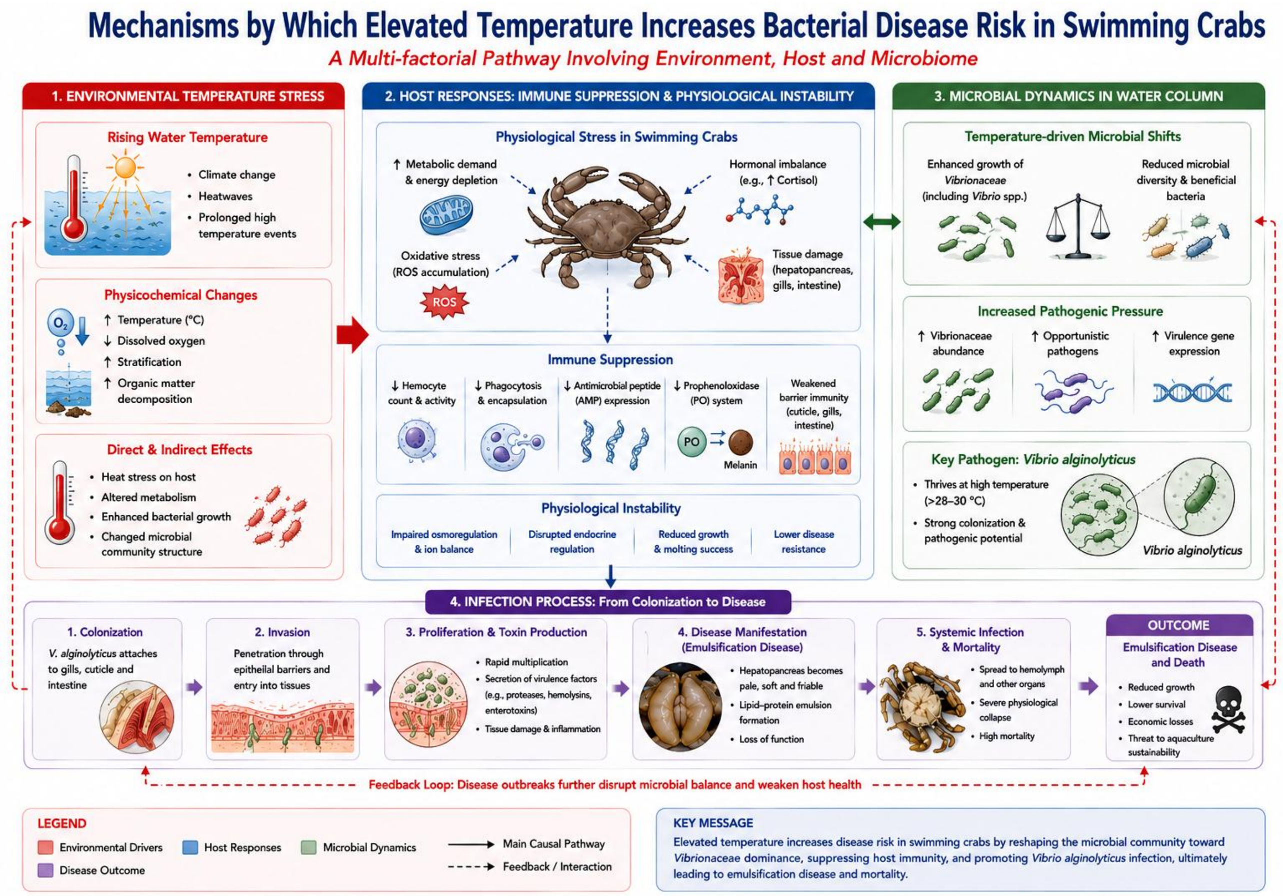


Figure 1 Mechanistic pathway linking high temperature to increased bacterial disease risk in swimming crab (*Portunus trituberculatus*) through host-microbiome interactions

### 4.3 Molting abnormalities and growth retardation

High temperature can disrupt molting rhythm in swimming crab, and the effect appears to depend on whether temperature remains within a favorable physiological window or exceeds it. Moderate warming often shortens intermolt periods and accelerates growth, but excessive heat becomes inhibitory: in crablets, 30°C improved molting frequency, growth, and feeding, whereas 34°C significantly reduced ecdysis frequency and slowed growth (Macario et al., 2025). A similar threshold pattern is evident during embryogenesis, where development remained normal at 27°C-29°C, but 31°C-33°C caused asynchronous development, diapause, increased mortality, and sharply reduced hatching success (He et al., 2022).

Current molecular evidence indicates that temperature affects molting through endocrine and metabolic regulation rather than through growth alone. In *P. trituberculatus*, silencing either TRPA1 paralog significantly prolonged the molting interval, and abnormal temperatures altered molting timing through changes in endocrine regulators and metabolic enzymes (Qian et al., 2025). Because successful molting also depends on intact molt signaling and adequate nutritional support, any heat-induced disruption of endocrine coordination is likely to interact with other culture stressors; consistent with this, cholesterol nutrition promotes ecdysone signaling, molting rate, and growth, indicating that growth retardation under heat stress is closely tied to impaired molting physiology rather than to reduced size gain alone (Zhu et al., 2022).

## 5 Key Health Management Techniques

### 5.1 Water quality regulation and farming environment optimization techniques

Under high-temperature conditions, water quality regulation should prioritize the stabilization of temperature, dissolved oxygen, pH, and ammonia, because rapid fluctuation in these parameters increases mortality risk and disease susceptibility in aquaculture systems. In swimming crab culture, prolonged summer deterioration of seawater quality can lengthen water-exchange intervals and expose crabs to sustained ammonia stress, while broader aquaculture evidence shows that instability in dissolved oxygen, pH, and temperature directly elevates the risk of production loss. (Lu et al., 2022; Flores-Iwasaki et al., 2025). Ammonia control and ecological optimization are especially important in intensive ponds during hot periods. In *Portunus trituberculatus*, long-term ammonia exposure above 15 mg/L for 15 days severely damages the hepatopancreas and compromises cellular stress responses, indicating that high-temperature management must include measures that reduce organic loading and improve nitrogen processing. Integrated pond regulation can help: nutrient-dynamics modeling showed that residual feed released 41.43% of total feed-derived carbon to the water, while adding razor clams at an appropriate density improved comprehensive water quality in swimming crab-shrimp systems (Lu et al., 2022; Yao et al., 2025).

### 5.2 Nutritional fortification and immune enhancement strategies

High temperature disrupts nutrient metabolism, increases oxidative stress, and suppresses immune function in crabs, so dietary fortification should focus on antioxidant and immunomodulatory additives. Evidence from chronic heat-stress experiments in crabs shows that elevated temperature increases reactive-oxygen-species-related damage and depresses survival, whereas nutritional intervention can partly restore antioxidant defenses and immune performance (Liu et al., 2023; Wang et al., 2024). Among the tested additives, yeast culture and targeted amino acid or vitamin supplementation appear especially promising for heat-stress mitigation. In juvenile Chinese mitten crab, 3.2 g/kg yeast culture improved survival, antioxidant enzyme activity, immune indices, and gut integrity under chronic heat stress, while high dietary methionine improved survival and reduced oxidative stress and apoptosis at 30°C; similarly, vitamin C at about 133.94-144.81 mg/kg enhanced nonspecific immunity and antioxidant capacity in mud crab. These findings support the use of fortified diets to maintain physiological resilience in swimming crab farming during hot seasons, although direct validation in *P. trituberculatus* under pond heat stress is still limited (Wang et al., 2024).

### 5.3 Intelligent monitoring and precision farming management techniques

Intelligent monitoring is increasingly central to high-temperature aquaculture management because manual sampling cannot detect sudden changes in temperature, dissolved oxygen, pH, and ammonia quickly enough for timely intervention. Reviews of aquaculture IoT systems show that real-time sensor networks improve growth, reduce mortality, and enable rapid detection of atypical water-quality conditions, while low-cost monitoring platforms can provide continuous parameter tracking with reduced labor input (Shete et al., 2024; Flores-Iwasaki et al., 2025). For swimming crab culture under thermal stress, the practical value of precision management lies in linking real-time sensing with threshold-based control and predictive intervention. Recent aquaculture studies report that automated systems can trigger oxygenation and pH adjustment during warm periods, maintaining survival above 90%, and sensor architectures can be adapted to control temperature, pH, and ammonia through pumps or heaters once preset thresholds are exceeded. Therefore, intelligent farming for swimming crab should integrate continuous sensing, early-warning models, and automated response functions to reduce the lag between environmental deterioration and management action (Zein et al., 2023; Baena-Navarro et al., 2025).

## 6 Case Study: Health Management Practices for Swimming Crab During High-Temperature Seasons

### 6.1 Overview of the case study farming area and high-temperature characteristics

The case study area can be characterized as a semi-closed coastal pond farming system for *Portunus trituberculatus* operating under intensive or polyculture conditions, where water exchange is relatively limited and environmental regulation depends strongly on in-pond management. In a representative integrated pond in Zhoushan, Zhejiang, the culture area was 1.33 ha with an average water depth of 1.2 m, salinity ranged from 14.5 to 19.0, and water exchange occurred only 1-2 times per month, which is consistent with management conditions that can magnify summer water-quality stress (Dong et al., 2022). Microbial evidence from semi-closed polyculture ponds likewise shows lower α-diversity under limited water exchange, indicating that enclosed high-temperature culture areas are ecologically sensitive and require close environmental control (Huang et al., 2024).

High-temperature exposure in such farming areas is both seasonal and biologically consequential. In early autumn culture, pond water is commonly around 30°C and can occasionally reach 33°C, while experimental evidence indicates that embryonic development remains relatively normal below 31°C but deteriorates above that threshold, with increased mortality and reduced hatching at 31°C-33°C (He et al., 2022). Elevated temperature also alters behavior and production risk in juvenile or adult crabs, because 30°C significantly increased aggressiveness and reduced behavioral predictability, while chronic summer heat in crab aquaculture more broadly is associated with oxidative stress, immune disturbance, and greater disease pressure (Liu et al., 2023).

### 6.2 Implementation process of health management measures

The implementation of health management during high-temperature seasons should begin with continuous water-quality regulation, especially for temperature, dissolved oxygen, pH, and ammonia. Real-time aquaculture monitoring studies show that IoT-based systems can continuously track these parameters and support rapid intervention when conditions deviate from preset thresholds, while broader sensor reviews indicate that such systems reduce mortality risk and improve the detection of atypical total ammonia nitrogen events (Shete et al., 2024; Flores-Iwasaki et al., 2025). For swimming crab ponds, this monitoring should be paired with restrained feeding, timely removal of residual feed, and controlled water exchange, because nutrient-dynamics simulations show major nutrient release from uneaten feed and summer seawater deterioration can prolong exchange intervals and intensify ammonia exposure (Dong et al., 2022; Lu et al., 2022).

A second part of the implementation process is ecological and biological stress reduction. Appropriate integrated culture can be used to improve the pond environment, because adding razor clams at suitable density improved water quality indices in swimming crab-shrimp systems, while microbial studies in swimming crab ponds suggest that potential pathogens such as Vibrio, Photobacterium, and Flavobacterium deserve focused surveillance during culture (Huang et al., 2024; Yao et al., 2025). At the animal level, stress buffering can be strengthened through environmental and nutritional measures: sand or PVC enrichment improved survival and reduced stress responses in *P. trituberculatus*, and heat-stress studies in crabs show that dietary supplementation such as yeast culture can improve survival, antioxidant status, immune performance, and gut health under prolonged thermal load (Xiong et al., 2024; Wang et al., 2024).

### 6.3 Evaluation of application effects and summary of experiences

The application effects of these measures can be evaluated from the perspectives of water stability, physiological protection, and production performance. Ammonia management is especially important, because environmentally relevant ammonia exposure suppresses energy metabolism, increases oxidative damage, and impairs reproduction in the hepatopancreas of female swimming crab, while long-term exposure above 15 mg/L for 15 days causes severe hepatopancreatic damage and depressed cellular stress responses (Meng et al., 2021; Lu et al., 2022). These findings indicate that health management is effective when it prevents the combined rise of temperature and ammonia rather than treating them as separate hazards.

Experience from related aquaculture systems suggests that integrated monitoring and timely correction can produce clear management benefits, but outcomes still depend on keeping heat exposure within the species' physiological tolerance window. Predictive IoT-ML systems in tropical ponds maintained survival above 90% through continuous monitoring and repeated corrective interventions, and postharvest temperature-control studies in swimming crab products similarly show that low-temperature handling suppresses microbial growth and quality deterioration (Chen et al., 2023; Baena-Navarro et al., 2025). Overall, the main practical lessons are to monitor key water variables continuously, reduce organic and ammonia loading before stress accumulates, combine ecological regulation with animal-level stress mitigation, and respond early once pond temperature approaches 30°C-31°C, because risk rises sharply beyond that range (He et al., 2022; Lu et al., 2025) (Figure 2).

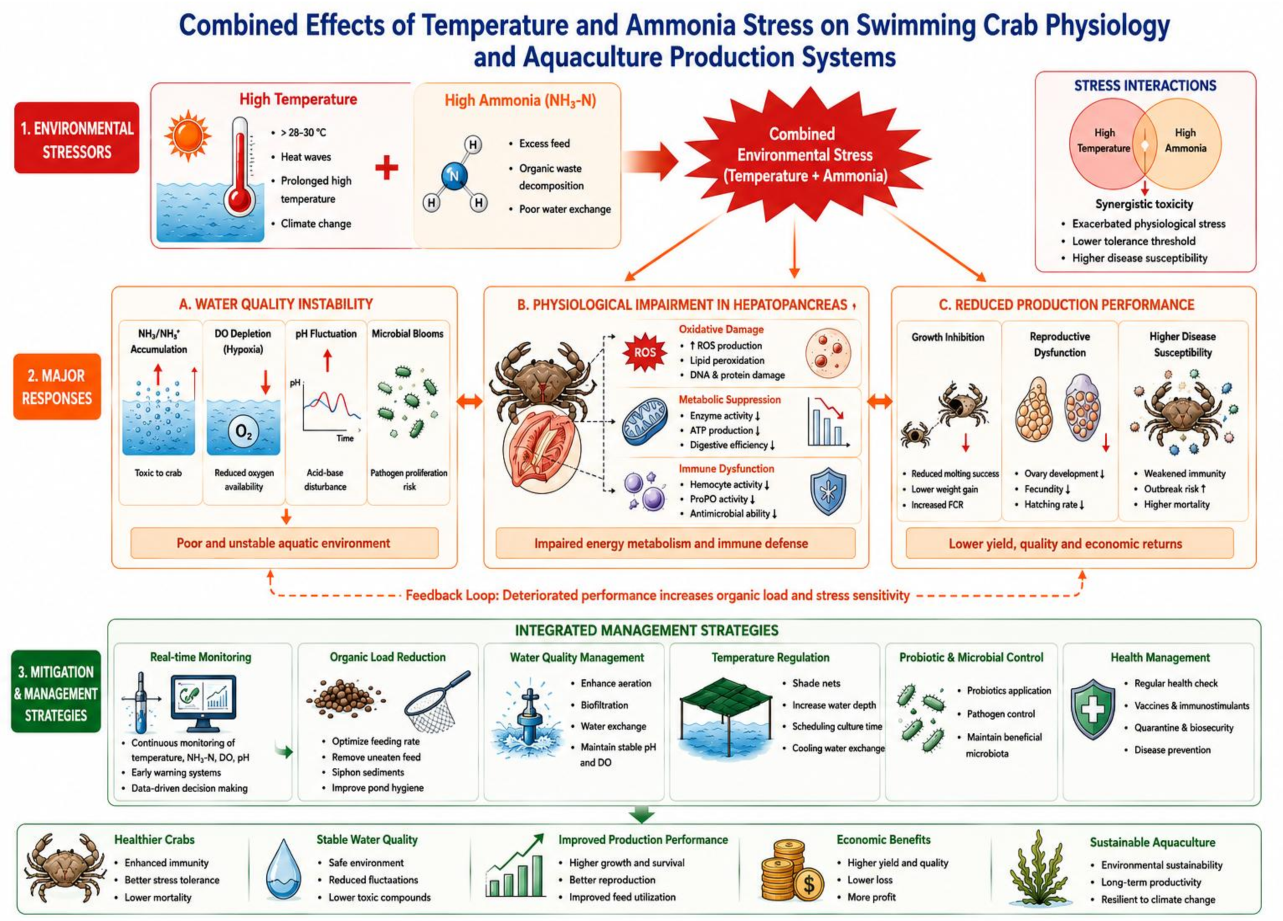


Figure 2 Environmental threshold levels and associated physiological risks in swimming crab aquaculture

## 7 Challenges in Health Management Under High Temperature

### 7.1 Management pressures arising from frequent extreme high-temperature events

Frequent extreme high-temperature events intensify the difficulty of maintaining the physiological stability of swimming crab culture systems because temperature directly affects crustacean metabolism, growth, moulting, immunity, and survival, while climate warming is increasing the frequency of damaging thermal exposure in aquaculture environments (Qian et al., 2024; Daunde et al., 2025). For swimming crab specifically, high temperature can disrupt energy metabolism, and severe stress is especially likely when elevated temperature is combined with air exposure, indicating that routine operations such as handling, grading, and transport become riskier during hot periods.

Extreme heat also creates management pressure by pushing crabs toward ecological and physiological thresholds beyond which recovery becomes difficult. In a related portunid crab fishery, juveniles became most susceptible when summer temperatures exceeded 24°C and conditions became clearly detrimental above 26°C, showing how short periods of abnormal warming can impair recruitment and survival. At the behavioral level, elevated temperature increases aggressiveness in *Portunus trituberculatus*, which can aggravate interference, injury, and cannibalism risk under high-density farming conditions (He et al., 2025).

### 7.2 Limitations in health monitoring and disease early-warning technologies

A major challenge under high-temperature conditions is that health deterioration often develops before farmers can identify it with conventional farm surveillance. Aquatic animal disease diagnostics still rely heavily on visual observation and traditional laboratory methods, while rapid kits and field-deployable tools remain insufficiently mature for routine farm use. Although CRISPR-, biosensor-, and LAMP-based tools are being developed, current field applications still face limitations in sensitivity and specificity, reducing their reliability for early warning during fast-moving heat-associated disease events (Bohara et al., 2023).

The second limitation is that effective early warning under heat stress requires integrated environmental forecasting, yet such systems remain uncommon in aquaculture practice. Temperature-sensitive marine diseases can be monitored using surveillance tools based on environmental temperature outlooks, and these tools can help target monitoring and management actions. However, outbreak risk is driven by nonlinear interactions among temperature, salinity, oxygen, pH, and host-pathogen factors, which makes prediction difficult for traditional approaches even though newer machine-learning systems show promise (Xie et al., 2025).

### 7.3 Lag in the development of integrated management systems and standardization

Integrated management systems for coping with high temperature in swimming crab farming still lag behind the needs of increasingly intensive production. Intensification raises stress through crowding, waste accumulation, and water-quality deterioration, and successful high-density culture depends on continuous balancing of biological and environmental variables that many farms still cannot achieve consistently (Emerenciano et al., 2022). This means that heat management cannot be treated as a single-factor issue, because elevated temperature interacts with oxygen, water quality, stocking density, and biosecurity failures to amplify health risks (Hapsari et al., 2025).

Standardization also remains limited because existing intelligent and integrated systems are still fragmented, species-specific, or insufficiently translated into broadly applicable farm protocols. Recent intelligent aquaculture systems can dynamically regulate temperature and oxygen using real-time stress feedback and can reduce chronic stress or disease incidence while improving operational performance, but these results mostly come from experimental systems in fish or shrimp rather than standardized frameworks for swimming crab culture (Nie et al., 2025). Likewise, integrated multi-trophic models such as shrimp-crab polyculture improve resource use and water-quality management potential, yet adoption depends strongly on local conditions, indicating that unified standards for high-temperature health management remain underdeveloped (Chang et al., 2020).

## 8 Conclusions and Future Perspectives

Current research shows that high temperature disrupts health homeostasis in *Portunus trituberculatus* at multiple levels, including energy metabolism, behavior, and cellular protection. Elevated temperature increases lactate accumulation, depresses ATP-related energy status, and can create a mismatch between energy demand and supply, especially when crabs are also exposed to air, which helps explain stress-induced mortality during culture and handling. In parallel, temperature elevation intensifies agonistic interactions and cannibalism risk, with fighting frequency and duration rising as temperature increases, indicating that thermal stress management must include both physiological and behavioral regulation.

Mechanistic work has further expanded this framework from phenotype to molecular regulation. Multi-omics evidence indicates that warming enhances aggressiveness through coordinated activation of energy metabolism and neural signaling pathways, while recent gene-level studies suggest that temperature perception in swimming crab involves broad induction of transient receptor potential channel genes under acute thermal stress. Together, these advances show that high-temperature health management is no longer limited to maintaining survival, but increasingly targets early stress recognition, metabolic stabilization, and the reduction of secondary risks such as injury, hypoxia, and immune imbalance.

The next stage of technology development should prioritize real-time, data-driven monitoring systems that can detect environmental deterioration and disease risk before mass losses occur. Recent aquaculture studies show that integrated IoT platforms can continuously track key variables such as pH, dissolved oxygen, and redox conditions, while machine-learning models can convert these data into disease prediction and automated warning outputs for farm management. More broadly, intelligent aquaculture frameworks that combine sensors, big-data processing, and AI-based decision systems appear well suited for swimming crab farming under heat stress, because they can shift management from experience-based reaction to evidence-based prevention.

A second development direction is rapid and field-deployable health diagnostics linked with stress biomarkers and epidemiological forecasting. Emerging aquamedicine tools, including biosensors, sequencing, CRISPR-based assays, drones, and AI-assisted monitoring, have already improved the speed of pathogen detection and farm surveillance, but broader adoption still requires lower-cost kits and better farmer training. In parallel, predictive systems that integrate surveillance with environmental drivers are becoming increasingly feasible; machine learning models using real-time or near-real-time environmental data now provide scalable outbreak forecasting frameworks that could be adapted to swimming crab pathogens under high-temperature conditions.

In the context of climate change, sustainable swimming crab aquaculture will depend on combining farm-level health management with broader adaptation planning. Reviews across aquaculture systems show that rising temperature alters physiology, feeding, immunity, and disease dynamics, while prolonged warming increasingly threatens productivity and sustainability, making adaptation an immediate rather than future requirement. For crustacean farming specifically, resilience pathways increasingly center on selective breeding, species or system diversification, dietary intervention, and technological upgrading, because thermal sensitivity affects growth, moulting, immune response, and survival across cultured taxa.

Long-term sustainability also requires climate-resilient production models supported by governance, forecasting, and ecological safeguards. Recirculating or integrated systems, environmental control strategies, and planned adaptation measures can reduce exposure to climate stressors, but their success depends on timely environmental information, regional planning, and policy support rather than farm-level action alone. At the same time, future development should avoid a narrow focus on productivity, because intelligent and genetic technologies can create ecological or animal-health tradeoffs if they are applied without localization, biodiversity protection, and sustainability oversight.

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