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Health Management Strategies for Large Yellow Croaker During High-Temperature Seasons

Manman Li
Hainan Institute of Biotechnology, Haikou, 570206, Hainan, China
Corresponding author: Manman.li@hibio.org
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Abstract High-temperature stress has become one of the most critical environmental constraints affecting marine aquaculture under ongoing climate warming, particularly for economically important species such as large yellow croaker (*Larimichthys crocea*). This review synthesizes current knowledge on the impacts of elevated temperature on physiological functions, disease susceptibility, and overall health performance of large yellow croaker, and evaluates integrated management strategies for mitigating thermal stress in aquaculture systems. High temperatures disrupt metabolic homeostasis, leading to increased energy expenditure, impaired respiratory and osmoregulatory functions, and reduced growth efficiency and feed utilization. At the immune level, thermal stress weakens host defense mechanisms, alters inflammatory responses, and promotes gut microbiota dysbiosis, thereby increasing the risk of bacterial and viral disease outbreaks. In response, environmental regulation strategies such as water temperature control, dissolved oxygen optimization, and water quality management are essential for maintaining system stability. Nutritional interventions, including optimized protein-energy balance and functional feed additives such as probiotics and immunostimulants, further enhance stress resilience. In addition, advances in health monitoring and early warning technologies, including physiological indicators and molecular diagnostics, provide new opportunities for precision aquaculture management. This review highlights the importance of integrated "environment-nutrition-management" frameworks and proposes future directions for intelligent and climate-resilient aquaculture systems for large yellow croaker.
Keywords High-temperature stress; Large yellow croaker; Marine aquaculture; Health management; Climate change

1 Introduction

Large yellow croaker (*Larimichthys crocea*) is one of China's most important marine aquaculture species, highly valued for its taste, nutritional quality, and strong market demand, and its cage-culture production has led the national marine fish sector for many years. However, rapid expansion of its farming has been accompanied by germplasm degradation, reduced disease resistance, and inconsistent product quality, threatening sustainable development of the industry (Han et al., 2025). As a warm-water coastal species with an optimal temperature of about 18 °C-25 °C and relatively high water-quality requirements, large yellow croaker is particularly sensitive to environmental fluctuations common in intensive mariculture. At the same time, intensive stocking and environmental change have driven frequent outbreaks of parasitic and bacterial diseases, making health constraints a central bottleneck for this species (Yao et al., 2024).

Rising water temperature linked to climate variability adds a further layer of risk to marine aquaculture systems. Comprehensive thermal biology assessment of cultured large yellow croaker shows that, although this species has relatively wide thermal limits and apparent plasticity, long-term exposure to 30 °C triggers energy redistribution, oxidative stress responses, and significant reductions in body weight, indicating trade-offs between growth, health, and heat tolerance under chronic heat stress (Wu et al., 2022). In floating sea-cage systems, shallow culture depth, high densities and limited space constrain behavioral thermoregulation and increase risks of hypoxia and disease infection during warm periods, leaving farms in main producing areas already at risk from summer heatwaves with in situ sea surface temperatures surpassing 30 °C. Case studies from other marine fish demonstrate that prolonged high temperatures (e.g., 35 °C in spotted seabass or extreme summer conditions in carp) precipitate oxidative damage, inflammation, and elevated mortality, highlighting generic mechanisms by which heat stress undermines fish health (Yang et al., 2024). For large yellow croaker, farm-level comparisons indicate that cage-reared fish can experience prolonged summer temperatures above the optimal range, accompanied by lower dissolved oxygen, higher mortality and poorer growth than fish maintained in mobile offshore ship systems that can track more favorable environmental conditions. International experience further shows that marine heatwaves and elevated temperatures can intensify harmful algal blooms and secondary infections, leading to geographically extensive fish kills and revealing the vulnerability of shallow, warm-water ecosystems where cultured fish often live near their upper thermal limits.

Within this climatic and environmental context, infectious diseases have become a major limiting factor for large yellow croaker aquaculture. Ciliate parasites such as Cryptocaryon irritans and scuticociliates are capable of causing rapid outbreaks, abnormal behavior, severe tissue damage and high cumulative mortalities in farmed stocks, with infection dynamics strongly influenced by stocking density and mariculture conditions. Recent investigations in large yellow croaker have documented mass-mortality events linked to scuticociliate infection, with experimental challenges producing over 70% cumulative mortality within one week, and transcriptomic analyses revealing extensive immune and metabolic disruption at the peak of mortality. Coinfections with blood-borne and myxosporean parasites have also been associated with mass mortalities in offshore net-cage systems, with year-round feeding and seasonal fish movements likely facilitating parasite circulation and transmission (Zhang et al., 2025). At the same time, bacterial pathogens such as *Vibrio* spp. and *Pseudomonas plecoglossicida* remain economically important, with outbreaks occurring across temperature ranges and sometimes outside previously recognized seasonal windows, underscoring the dynamic interaction between pathogens, host susceptibility, and changing environmental conditions. More broadly, infectious disease is recognized as a leading global constraint in aquaculture, causing multibillion-dollar losses annually, with disease emergence and antimicrobial resistance making traditional, treatment-focused approaches increasingly unsustainable (Wright et al., 2023).

These converging pressures make health management during high-temperature seasons a strategic priority for the large yellow croaker industry. General aquaculture experience emphasizes that the most predictable consequence of stress is immune suppression, leading to increased disease susceptibility and mortality, and therefore highlights the importance of controlling environmental stressors such as temperature, dissolved oxygen and stocking density through good husbandry and biosecurity practices rather than relying solely on therapeutic interventions. Preventive health strategies—combining optimized culture systems that avoid peak thermal stress, farm-level biosecurity, vaccination where available, functional feeds and probiotics, and microbiome-informed early-warning tools—are increasingly viewed as essential components of sustainable disease control frameworks that align with One Health principles. For large yellow croaker specifically, research on probiotics capable of inhibiting key bacterial pathogens, breeding for enhanced stress and temperature tolerance, and alternative farming systems that maintain fish within optimal thermal and oxygen ranges illustrate emerging pathways to strengthen resilience under warming scenarios. Systematically synthesizing these strands into health management strategies tailored to high-temperature seasons is therefore of great significance for safeguarding fish welfare, stabilizing production, and securing the long-term sustainability of large yellow croaker aquaculture.

2 Research Background and Mechanisms of High-Temperature Stress

2.1 Climate warming and marine heatwave ecological context

In recent decades, global ocean warming has driven a marked rise in the frequency, duration and intensity of marine heatwaves (MHWs), with the number of MHW days roughly doubling between 1982 and 2016. These extreme warm events are projected to intensify strongly under continued warming, greatly increasing the probability that coastal farming areas experience prolonged high-temperature anomalies. MHWs already cause broad ecological impacts, restructuring marine ecosystems and threatening biodiversity and ecosystem services that support fisheries. For exploited fish and invertebrates, annual high temperature extremes typically reduce biomass for most stocks and lower maximum catch potential, adding to long-term climate impacts (Cheung et al., 2021).

MHW impacts in productive boundary regions, such as the northeast Pacific, illustrate how biomass declines and rapid range shifts during heatwaves can be several times larger and faster than those driven by gradual warming alone. Such events impose "double strains" on fisheries management by overlaying acute shocks on chronic warming trends (Cheung and Frölicher, 2020). For aquaculture species, including large yellow croaker, extreme temperature episodes are becoming more frequent and intense, and temperature acts as the master abiotic factor controlling development and physiology across all life stages. Climate change-induced extremes drive changes in growth, metabolism, hemato-physiology and immune function, with impacts varying among species and depending on stress magnitude. Large yellow croaker farms in China's main production areas are already close to or within risky temperature regimes during summer. Field data show maximum sea surface temperatures around 30.1 ℃ and rapid warming rates in summer, exposing cage-reared croaker to summer heatwaves (Wu et al., 2022). Although thermal safety margins relative to lethal limits appear currently positive, prolonged exposure to 30 ℃ induces energy redistribution, oxidative stress, and reduced body weight, indicating sublethal performance costs under chronic heat.

2.2 Physiological and cellular mechanisms of thermal stress

At the organismal level, temperature increases act as potent acute and chronic stressors for fish. Rapid warming elicits typical primary and secondary stress responses, including catecholamine and cortisol release, followed by rises in blood glucose and lactate, and changes in osmolality and hematological variables. These reactions are superimposed on elevated metabolic rate under chronic warming, potentially compromising the capacity to cope with additional stressors and leading to long-term impacts on fitness. Acute upper thermal limits are governed by direct thermal effects on reaction rates, protein structures and membrane fluidity, which then propagate through cellular and organ-level pathways. In fish, these mechanisms include mitochondrial dysfunction, oxygen limitation in some species, and impaired excitability of neural and muscular cells, leading to loss of equilibrium, failed homeostasis and ultimately heat death (Ern et al., 2023).

The limiting pathways vary among species, life stages and thermal histories, implying that a single universal failure mechanism is unlikely. At the cellular level, high temperature commonly induces oxidative stress, inflammation and apoptosis. In rohu carp, partial-lethal thermal exposure elevates antioxidant defenses (e.g. reduced glutathione, catalase, superoxide dismutase expression) and heat shock responses (hepatic hsp70), yet these responses are insufficient to prevent lipid peroxidation, DNA fragmentation, and pro-inflammatory activation, leading to hepatotoxicity and partial mortality. Similarly, in pufferfish, high temperature elevates serum enzymes, triggers oxidative damage, and upregulates pro-apoptotic genes (p53, caspase-9, caspase-3), indicating caspase-dependent and p53-mediated apoptosis under thermal stress. For large yellow croaker, prolonged exposure to upper-range temperatures (e.g. 30 ℃) results in energy reallocation and oxidative adjustments. Experimental work shows that long-term high temperature reduces body weight and increases superoxide dismutase activity in gills, reflecting a trade-off between maintaining performance and mitigating oxidative stress (Wu et al., 2022). At the proteomic level, high-temperature stress in croaker liver alters thousands of proteins, with 442 differentially expressed proteins enriched in pathways related to translation, oxidative phosphorylation, ribosomes and lipid metabolism, indicating broad reprogramming of protein synthesis and energy use (Figure 1).

2.3 Overview of thermal stress response pathways in aquatic animals

Aquatic animals mount a conserved cellular stress response to temperature extremes that is centered on heat shock proteins (HSPs). In fish and shellfish, HSP families such as HSP70 and HSP90 act as molecular chaperones for protein folding, assembly, and protection against misfolding, and are upregulated not only by heat but also by hypoxia, toxins and infection. The HSP response contributes to thermotolerance and also modulates apoptosis, inflammation and immune function, linking environmental stress to disease resistance in finfish and shrimp (Jeyachandran et al., 2023). In teleost fish generally, HSP expression is induced in numerous tissues and cell types by both biotic (pathogens) and abiotic (heat, cold, contaminants) stressors, and is now recognized as a central component of the generalized stress response. In aquaculture, non-traumatic induction of HSPs (e.g. by mild heat or stimulants) is being explored as a strategy to enhance resilience, reduce handling trauma, and support vaccination and transport. For large yellow croaker specifically, multiple thermal stress pathways have been characterized.

Genome-wide analyses have identified 17 hsp70 genes organized into distinct evolutionary groups, with several showing significant upregulation under heat stress, indicating diversified but coordinated HSP-mediated defenses against temperature challenges. Liver transcriptome studies under heat and cold stress further reveal thousands of differentially expressed genes, with strong enrichment of energy metabolism and related pathways, confirming that temperature stress reshapes metabolic and stress-response networks at the transcriptional level. Signal-transduction cascades such as p38 MAPK also participate in croaker thermal responses.

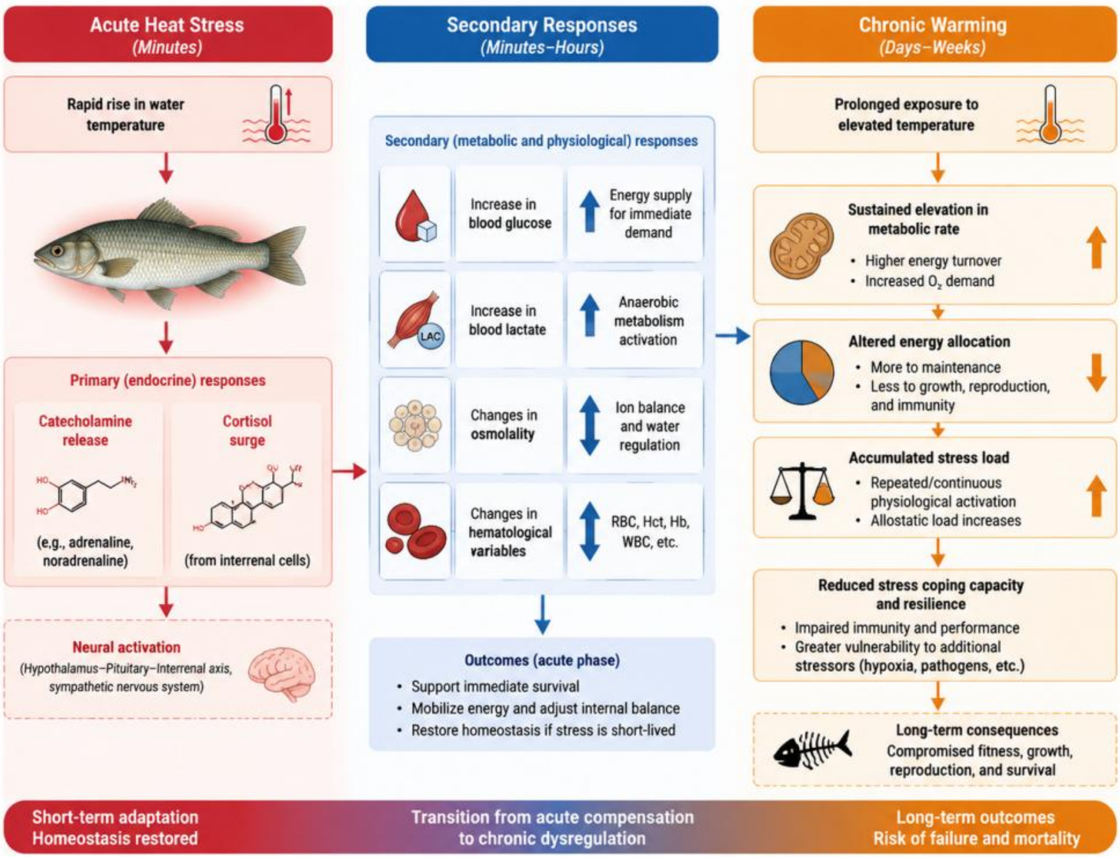

Figure 1 Organismal stress response pathways in fish under acute and chronic thermal stress

Note: Acute warming triggers endocrine activation (catecholamines and cortisol), followed by secondary metabolic responses, while chronic exposure leads to sustained metabolic elevation and reduced stress coping capacity

In a croaker kidney cell line, both cold (10 °C) and heat (35 °C) significantly upregulate p38 MAPK transcripts, and thermal exposure increases p38 phosphorylation together with transcription of HSP27 and caspase-3. Pharmacological inhibition of p38 MAPK suppresses HSP27 and caspase-3 induction, indicating that p38 mediates key branches of the heat shock and apoptotic response in this species. Genetic studies also show that acute heat tolerance (AHT) in large yellow croaker is polygenic, with genome-wide association identifying several significant SNPs and ~30 candidate genes, including heat shock factor 1, DnaJ homologs, Hikeshi and protein disulfide-isomerase A3 (Wu et al., 2021). Comparative analyses highlight the roles of blood-vessel regulation, heat shock response and endoplasmic reticulum stress response in inter-individual variation in AHT, providing a mechanistic basis for breeding heat-tolerant strains.

High-temperature seasons now unfold against a background of intensified marine heatwaves and chronic warming, exposing large yellow croaker to more frequent and severe thermal stress. At the organismal, cellular and molecular levels, heat challenges induce complex stress, oxidative, apoptotic and heat shock pathways that reshape metabolism and compromise growth and health. In large yellow croaker, detailed characterization of thermal limits, transcriptomes, proteomes, signaling cascades and genetic determinants of heat tolerance provides a solid mechanistic foundation for targeted health-management and selective-breeding strategies under a warming ocean.

3 Effects of High Temperature on Physiological Functions of Large Yellow Croaker

3.1 Changes in metabolic rate and energy allocation

High temperature reshapes liver metabolism of large yellow croaker, shifting how energy is produced and allocated. Proteomic analysis under high-temperature stress shows reduced protein synthesis and a transition from oxidative phosphorylation to glycolysis, alongside increased fatty acid biosynthesis and reduced fatty acid catabolism in the liver of thermally stressed fish (Zhang et al., 2023). Transcriptomic work further confirms that temperature stress in large yellow croaker broadly alters energy-metabolism pathways, with genes encoding key metabolic enzymes markedly up- or down-regulated in the liver.

Long-term exposure to high rearing temperatures redistributes energy away from somatic growth toward defense and maintenance. In large yellow croaker acclimated to 30 °C, body weight declines while oxidative stress markers such as gill superoxide dismutase activity increase, indicating a trade-off between growth and heat tolerance. Multi-omics analysis under summer heat shows that dietary inulin can partially rebalance this allocation by upregulating hepatic glycolysis and fatty-acid biosynthesis and enriching beneficial gut bacteria, thereby supporting energy production and growth under chronic thermal stress (Yin et al., 2026).

3.2 Disruption of respiration and osmoregulatory functions

High water temperature challenges gill function in teleosts, combining respiratory strain with osmoregulatory disturbance. In Atlantic salmon smolts, rapid warming to 24 °C in seawater causes complete mortality and severe ion-regulatory failure, with poor plasma ion control and depressed gill Na^+/K^+-ATPase activity, highlighting a temperature threshold beyond which osmoregulation collapses. Similar enzyme suppression occurs in juvenile goldfish, where elevated temperatures reduce gill Na^+/K^+-ATPase expression while inducing structural lesions such as lamellar fusion and epithelial detachment, implying impaired gas exchange and ionic balance under heat stress (Ngozichukwu and Rahman, 2025).

Transcriptomic analysis in Siberian sturgeon gills illustrates the mechanistic basis of these osmoregulatory disturbances. Heat stress elevates reactive oxygen species and tissue damage, while downregulating Na^+/K^+-ATPase α and upregulating multiple ion-transport genes involved in active ion absorption and passive efflux, indicating increased gill permeability and compensatory ion-transport adjustments (Yang et al., 2023). In other species, high-temperature exposure elevates antioxidant enzymes and heat-shock proteins in gills, yet oxidative and nitrative damage still develops, underscoring that respiratory and osmotic homeostasis remain vulnerable when temperatures exceed adaptive limits (Schleger et al., 2024).

3.3 Decline in growth performance and feed utilization efficiency

Long-term high temperatures generally depress growth performance once the thermal optimum is exceeded. In hybrid catfish, growth and feed utilization follow a quadratic response to temperature: performance peaks around 32 °C but falls sharply at 37 °C, where growth, feed efficiency, and tissue condition all deteriorate (Khieokhajonkhet et al., 2022). Studies on cherry salmon show a similar pattern: body weight, growth rate, feed intake, and feed efficiency are significantly higher at cooler 10 °C-14 °C than at 18 °C-22 °C, with 22 °C associated with poor feeding and impaired growth and health (Lee and Balasubramanian, 2023). These performance declines are tightly linked to metabolic costs and feed conversion. In cherry salmon, reduced feed efficiency at elevated temperatures is attributed to increased standard metabolic rate, which leaves less dietary energy available for growth under fixed ration sizes. Across other cultured species, higher rearing temperatures can require more feed per unit biomass gain and worsen nutrient deposition, as seen in growth-hormone transgenic Atlantic salmon reared at 16.5 °C, which show poorer feed conversion and less efficient omega-3 deposition than fish at cooler temperatures.

High temperatures in large yellow croaker culture shift liver metabolism toward glycolysis and altered lipid use, while long-term warming forces an energy trade-off away from growth and toward stress defense. Gill respiration and osmoregulation become fragile under heat, with Na^+/K^+-ATPase suppression, structural damage, and oxidative stress compromising gas exchange and ion balance. Across species, exceeding optimal temperatures consistently reduces growth performance and feed efficiency by raising metabolic costs and impairing nutrient utilization, highlighting the need to manage summer temperatures carefully in large yellow croaker aquaculture.

4 Disease Occurrence and Immune Alterations under High Temperature

4.1 Characteristics of bacterial and viral disease outbreaks

In large yellow croaker cage culture, bacterial diseases show clear seasonality, with vibriosis occurring mainly from June to October and peaking in July-August when water temperature is high; mortality can reach 30%-40%, and even 80% in severe cases. Under these warm, crowded conditions, *Vibrio alginolyticus* and *V. harveyi* proliferate, and high stocking density, environmental deterioration, and skin damage at high temperature are identified as major drivers of outbreaks.

Other pathogens show temperature-linked patterns that are crucial for health management. Visceral white nodule disease (VWND) caused by *Pseudomonas plecoglossicida* usually occurs at 16 °C-19 °C, but a virulent strain was shown to trigger outbreaks even at 12 °C, expanding the known risk window (Li et al., 2020). Temperature-dependent parasitic diseases have also been documented: Petalosoma infections appear at 23.0 °C-27.4 °C, while Cryptocaryon and Benedenia outbreaks are linked to late-summer temperatures around 27 °C-28.8 °C and become especially serious at 28.2 °C-28.5 °C.

4.2 Changes in immune-related enzyme activities and inflammatory responses

Multiple stressors related to intensive culture can mimic or interact with high-temperature stress by activating antioxidant and immune enzymes. Under long-term high stocking density, large yellow croaker show elevated liver SOD and CAT activities and increased HSP70/HSP90 and glutathione S-transferase gene expression, indicating chronic oxidative and cellular stress (Yu et al., 2024). During parasitic *Metanophrys* sp. infection, tissue- and time-specific shifts in SOD, CAT, MDA, lysozyme, and Na^+/K^+-ATPase activities in skin, gill, and liver reflect increased oxidative stress and activation of mucosal defenses over 0-72 h post-infection (Zhou et al., 2025).

Inflammatory signaling is strongly remodeled under infection and stress. Aeromonas hydrophila infection drives large changes in splenic transcriptomes, with many differentially expressed genes in Toll-like receptor, JAK-STAT, and MAPK pathways and marked shifts in inflammatory genes, highlighting a central role of inflammatory responses early in infection. At the cellular level, regulators such as Trim38 and farnesoid X receptor (FXR) modulate NF-κB-driven cytokine production and ER-stress-linked inflammation, suggesting that controlling these pathways can limit tissue damage during intense or prolonged inflammatory activation.

4.3 Mechanisms of gut microbiota dysbiosis

Pseudomonas plecoglossicida infection in large yellow croaker illustrates how disease and temperature-relevant stress can reshape gut communities and immunity. The pathogen colonizes the gut, elevates mortality, induces persistent up-regulation of pro-inflammatory cytokines (TNF-α1, TNF-α2, IL-1β) and IL-10, and triggers only transient increases in non-specific immune enzymes at early stages (Li et al., 2020). This infection leads to irreversible disruption of the gut microbiota, with infection status explaining a substantial fraction of community variation; dysbiosis is statistically linked to immune activity and is proposed as a direct cause of rising mortality.

Findings from other fish support common mechanisms by which heat stress drives dysbiosis and barrier damage, which are likely relevant to large yellow croaker in warm seasons. In rainbow trout exposed to acute heat stress, rising temperatures reduce gut microbial diversity, shift community composition, and are tightly associated with altered serum metabolites (amino acids, vitamins, short-chain fatty acids); concurrent damage to intestinal structure, barrier integrity, antioxidant capacity, and increased pro-inflammatory cytokines indicates that microbiota changes and metabolic dysfunction jointly mediate heat-induced intestinal injury. Similarly, high-temperature exposure in rainbow trout disrupts epithelial and goblet cells, increases IL-1β and IL-8 expression, and alters microbiota composition and KEGG pathways related to immune function, underscoring the tight crosstalk between gut immunity and microbiota under thermal stress (Zhao et al., 2023).

5 Environmental Regulation Strategies in Aquaculture Systems

5.1 Water temperature control and stratification management techniques

Fish in thermally variable coastal systems naturally adjust depth and habitat to remain near preferred temperatures, moving deeper during warm summers and shifting as stratification reverses in winter. This behavior indicates that aquaculture systems for large yellow croaker should minimize sharp temperature gradients and provide access to thermally suitable layers, especially during peak summer surface warming. Reviews on extreme temperature events in aquaculture suggest that structural modifications such as increased water depth or coverings, and the use of recirculating systems, can buffer fish from temperature spikes (Islam et al., 2021).

Experimental work on recirculating ponds shows that optimizing the layout, perforation rate, and angles of water supply pipelines can markedly improve thermal uniformity and weaken stratification (Zhang et al., 2024). In larger water bodies, selective withdrawal strategies that adjust intake depth can raise downstream water temperatures during critical spawning and growth periods while weakening reservoir stratification, offering a model for managing inflow and outflow depths in large pond or reservoir-based aquaculture (Wang et al., 2024).

5.2 Dissolved oxygen optimization and water circulation system design

In feed-based ponds, major oxygen sources are phytoplankton photosynthesis and mechanical aeration, while fish and microbial respiration constitute dominant sinks, leading to high daytime oxygen but dangerously low nighttime levels under warm, eutrophic conditions. Reviews of aeration technologies emphasize that selecting efficient aerators and correctly sizing and positioning them is crucial to maintain optimal dissolved oxygen in intensive systems.

Empirical studies in brackish ponds demonstrate that paddle-wheel aerator placement, as well as seasonal variation in total dissolved and suspended solids, strongly influence mixing intensity, water velocities, and oxygen transfer rates, and that data-driven models can forecast dissolved oxygen with high accuracy to guide aeration scheduling (Ramesh et al., 2024). In RAS, simple pipeline diffused aeration systems using pure oxygen have been shown to substantially increase outlet dissolved oxygen with predictable performance based on pipe length, inlet oxygen, and contact time, allowing controllable DO regulation during periods of high temperature and metabolic demand (Ji et al., 2024).

5.3 Water quality regulation and pollutant control strategies

Dynamic modeling of RAS highlights that ammonia, nitrite, nitrate, dissolved oxygen, and pH are tightly linked to fish metabolism, feeding intensity, biofilter performance, and water exchange, and that strengthening biological filtration and oxygenation is key to preventing toxic accumulations (Udayakumar et al., 2025). Reviews of recirculating systems detail that particulate matter, nitrogen pollutants, phosphate, carbon dioxide, antibiotics, steroids, and heavy metals can build up and compromise fish health, so integrated treatment units must filter or degrade these substances and recycle purified water (Li et al., 2023).

Biological approaches have been particularly effective for nitrogen control. Bacteria-microalgae associations in recirculating ponds significantly reduced total nitrogen, ammonia, and nitrite while improving fish production, supported by shifts in microbial communities toward nitrification and denitrification pathways. Similarly, assembled bacterial consortia of Bacillus and Pseudomonas species have efficiently converted ammonia to nitrite and further to less toxic nitrate in aquaculture wastewater, greatly improving fish survival compared with untreated controls. Reviews focused on Bacillus species confirm their broad capacity to modulate physical and chemical water quality parameters, including nitrogenous species, heavy metals, and microbial balance, offering a cost-effective tool for maintaining stable environments during stressful warm periods (Figure 2).

6 Nutritional and Feeding Management Strategies

6.1 Adjustments of energy and protein requirements under high temperature

High summer temperatures increase metabolic costs, so diets must supply sufficient digestible energy while avoiding excessive metabolic and oxidative burden. Recent reassessment of large yellow croaker nutrition in net pens indicates that crude protein levels of about 490-520 g/kg combined with 90 g/kg lipid support fast growth, high nitrogen retention, and appropriate body lipid with normal antioxidant capacity, suggesting this range as a baseline for high-demand periods (Chen et al., 2023). For thermal stress conditions, evidence from spotted seabass shows that protein requirements can shift with temperature, with slightly lower optimal protein at 33 ℃ than at 27 ℃, indicating that heat alters nutrient metabolism and the efficiency of protein use.

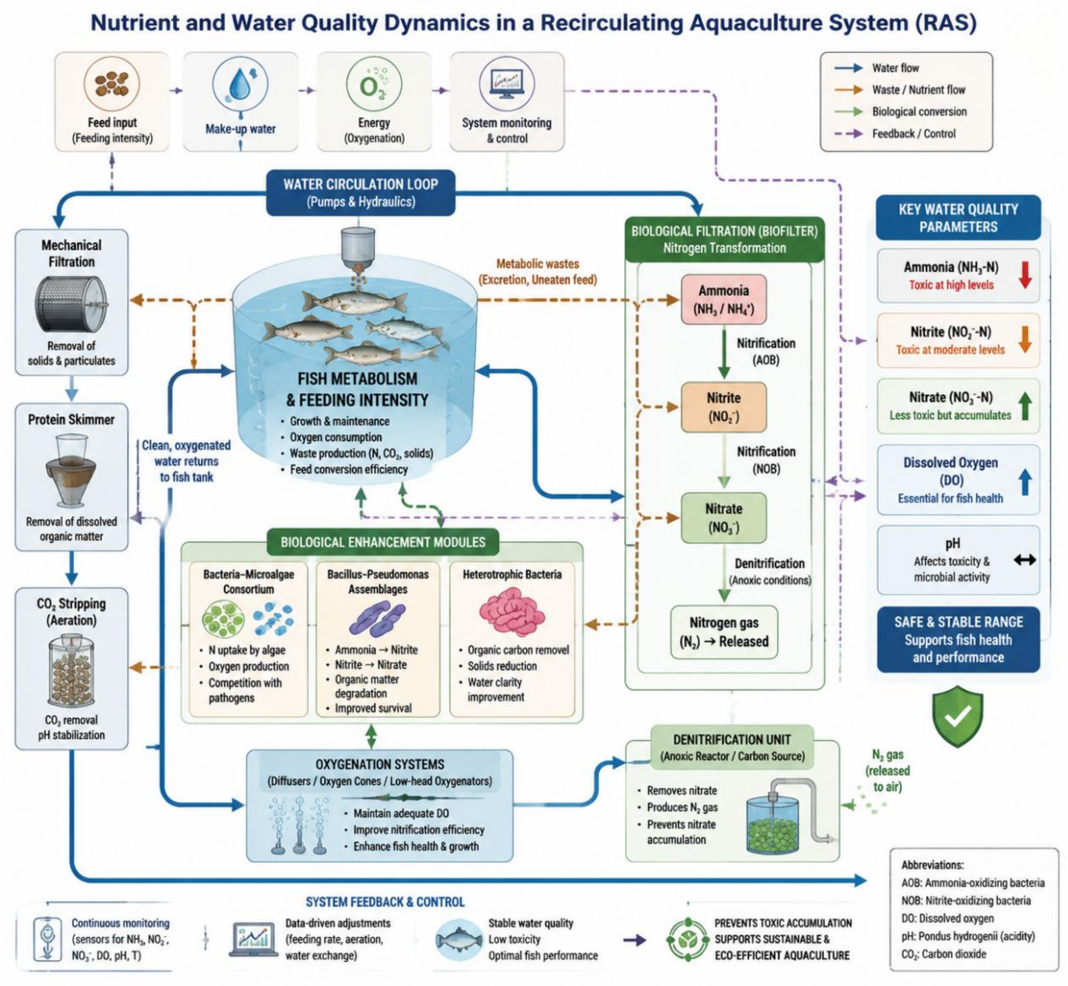

Figure 2 Systems-level interactions in recirculating aquaculture systems (RAS), illustrating feedback loops between fish metabolism, nitrogen cycling processes, and biological treatment units including nitrifying bacteria, bacterial consortia, and microalgae

Balancing protein with non-protein energy is critical to spare protein for growth and limit catabolic stress under high temperature. In large yellow croaker, elevating dietary lipid from 60 to 90 g/kg improves weight gain and nitrogen retention, but further increase to 120 g/kg does not enhance performance, implying an upper threshold for effective energy supplementation (Chen et al., 2023). The same study estimates a suitable dietary energy content around 19 MJ/kg and notes that when energy needs are satisfied, additional lipid no longer induces protein-sparing, which is important when setting rations during hot seasons.

6.2 Functional feed additives

Under high-temperature, high-density culture, functional additives that stabilize immunity and gut health become key complements to macronutrient adjustments. Broad aquaculture evidence shows that bio-friendly supplements such as probiotics, prebiotics and synbiotics can improve growth and stress mitigation while modulating intestinal microbiota and immune competence, thereby reducing reliance on antibiotics. Reviews on aquaculture feed additives further emphasize that immunostimulants (e.g., β-glucans, nucleotides) and prebiotics regulate innate defenses and gut barrier function, with typical inclusion ranges of a few g/kg diet (Okon et al., 2025).

For large yellow croaker specifically under summer heat stress, dietary inulin has emerged as a promising prebiotic strategy. A two-month trial across July-September showed that an inulin level around 0.4% significantly improved growth, accompanied by up-regulation of glycolysis and fatty-acid biosynthesis genes and increased metabolites supporting energy production. Inulin also reshaped the gut microbiota with enrichment of beneficial bacteria such as Lactobacillus and higher levels of short-chain fatty acids and amino acids, suggesting enhanced nutrient absorption and thermal stress tolerance (Yin et al., 2026).

6.3 Optimization of feeding strategies and regulation of feeding behavior

Feeding strategy must adapt to the combined effects of temperature, water quality, and fish appetite to avoid over- or under-feeding during hot periods. Under experimentally imposed high-temperature stress in common carp, an intermittent strategy of feeding every third day produced higher weight gain, better specific growth rate, lower feed conversion ratio, and enhanced digestive enzyme activities compared with daily feeding, while also improving antioxidant status. Behavioral analysis in Pangasius culture cages likewise shows that optimal feeding rates depend on weather-driven changes in temperature, pH, and dissolved oxygen, with higher intake feasible on warm, sunny days but reduced rations recommended during cloudy or rainy conditions to avoid waste and water quality deterioration (Yashashvi et al., 2023).

Technological tools for monitoring and regulating feeding behavior can further refine summer feeding management. Reviews of intelligent feeding control highlight that traditional fixed schedules often fail to match dynamic appetite and can lead to excessive or insufficient feeding, whereas behavior-based automatic systems use models, acoustic sensing, or computer vision to determine real-time demand. A complementary line of work on automatic recognition of feeding behavior shows that many methods can quantify feeding intensity, but accuracy in complex environments still needs improvement, pointing to the potential of data fusion and deep learning for precise control under fluctuating summer conditions (Li et al., 2020).

7 Case Study: Practical Health Management of Large Yellow Croaker under High-Temperature Conditions

7.1 Typical high-temperature aquaculture regions and system setup

Large yellow croaker farming is concentrated in warm, shallow coastal waters of southeastern China, where cage culture has become the dominant production mode and main source of national mariculture output. Typical cage-culture districts in Fujian such as Jiaocheng, Shacheng and Xiapu show regional differences in growth performance, with Xiapu fish achieving the highest asymptotic size and weight, suggesting that local hydrology and thermal regimes strongly affect production efficiency (Chen et al., 2020).

Summer sea surface temperatures in these regions increasingly approach 30 ℃, narrowing thermal safety margins and challenging traditional floating cage systems that are shallow and restrict behavioural thermoregulation (Figure 3). Review work on large yellow croaker aquaculture highlights that floating sea-cages remain the main farming model, but deep-sea cages and indoor recirculating systems are being promoted to better simulate natural habitats and buffer environmental extremes, providing alternative setups for high-temperature seasons (Thanhhoa et al., 2020).

7.2 Application effects of integrated management measures

Case comparisons between nearshore cages and a mobile offshore aquaculture ship demonstrate how integrated environmental management directly improves health outcomes during warm months. The ship system maintained water temperatures mostly within 21.5 ℃-28.5 ℃ and dissolved oxygen of 7.2-12.8 mg/L, with low ammonia and relatively low bacterial and Vibrio counts, and achieved 99.02 % survival and markedly higher growth than cages. By contrast, nearshore cages experienced prolonged high temperature and chronically low dissolved oxygen, conditions linked to oxidative stress, impaired digestion and immunity, and higher mortality, underlining the value of mobile or deeper systems that can track optimal water masses (Yu et al., 2023).

Nutritional and stock-management measures complement environmental control in mitigating heat stress. Long-term high stocking density elevates cortisol, antioxidant and stress-related enzymes, while depressing immune parameters, and authors recommend controlling final density to 14.41-18.71 kg/m^3 in intensive systems to preserve health and product quality (Yu et al., 2024). During summer heat, targeted functional feeds such as inulin or fulvic acid have significantly improved growth, survival and thermal resilience, partly by enhancing energy metabolism pathways and beneficial gut microbiota, indicating that nutrition can offset some high-temperature pressures when integrated with environmental and density management.

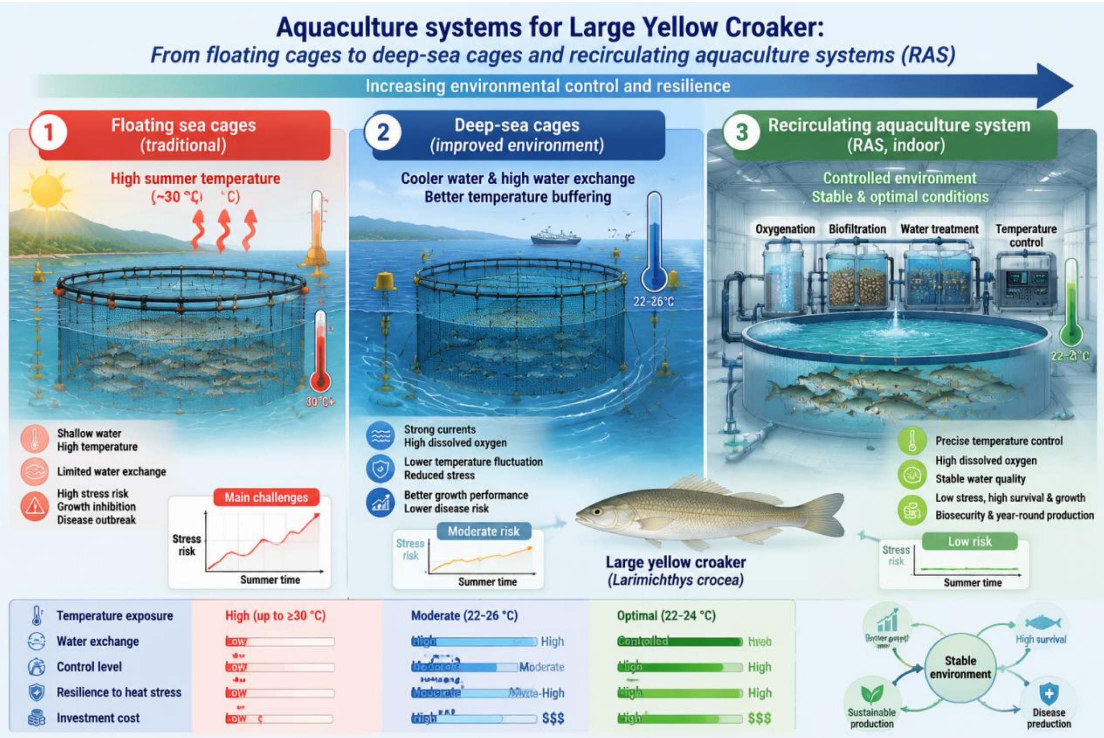

Figure 3 Comparison of farming systems for large yellow croaker, illustrating traditional floating cages, deep-sea cages, and recirculating aquaculture systems (RAS) as adaptive responses to environmental stress

7.3 Comparative analysis of success and failure cases and experience summary

Comparisons across culture modes and regions reveal clear patterns distinguishing successful high-temperature management from failure. Offshore ship aquaculture, operating within moderate temperature and high oxygen ranges and maintaining low nitrogen and bacterial levels, achieved near-complete survival and superior flesh composition, whereas static nearshore cages exposed to heat and hypoxia suffered slower growth and higher mortality, illustrating the cost of inadequate environmental buffering. Regionally, heavily eutrophic areas with low pH and dissolved oxygen, such as one major cage region where nutrients and heavy metals were highest, present higher ecological risk and poorer fish quality than better-managed sites, emphasizing that pollution control is integral to heat-season health management (Chen et al., 2025).

Experience from thermal biology and breeding research further refines these practical lessons. Large yellow croaker show appreciable thermal plasticity and high formal thermal safety margins, yet prolonged exposure to 30 ℃ still causes energy reallocation, growth depression and oxidative stress, warning against relying solely on nominal tolerance when designing summer strategies. At the same time, genetic and seed selection work stresses the need to integrate traits such as disease resistance and environmental stress adaptation into breeding and to pair improved strains with intelligent environmental control, precision feeding and disease prevention, forming a comprehensive package for robust performance under future hotter summers.

8 Health Monitoring and Early Warning Technologies

8.1 Physiological indicators and behavioral monitoring techniques

High-temperature seasons demand noninvasive techniques that track physiological stress in large yellow croaker without adding further injury risk. A high-temperature stress study showed that cortisol in serum, skin mucus, and surrounding water followed a similar “rise then fall” pattern, peaking at 1.5 h, and that cortisol levels in these three media were highly correlated, supporting skin mucus and tank water as practical substitutes for blood sampling. Parallel measurement of MDA, IgM, and AKP in serum and skin mucus further indicates that oxidative damage and immune status can also be followed through mucus, enabling repeated monitoring during heatwaves without sacrificing fish.

Behavioral responsiveness provides another early window into stress before overt disease emerges. In large yellow croaker subjected to a brief net-restraint challenge, consistent differences in recovery latency and exploration activity revealed proactive and reactive coping styles, with faster-recovering fish showing lower plasma cortisol and higher IgM at 7 days after stress (Li et al., 2024). Hypoxia studies show that restlessness, constant floating, and increased respiratory rate are accompanied by up-regulation of muscular movement and energy-generation genes, linking observable behavior with defined molecular pathways, which could be exploited for automated video-based stress surveillance during warm, low-oxygen nights (Chen et al., 2024).

8.2 Molecular biology and pathogen detection methods

Rapid pathogen diagnosis is essential because co-infections and temperature fluctuations can drive sudden mortalities in marine farms. A broad review of bacterial fish diseases emphasizes that molecular assays such as conventional PCR, real-time PCR, multiplex PCR, LAMP, microarrays, and sequencing provide faster and more sensitive identification of septicemic agents than traditional culture, supporting early intervention and targeted antimicrobial use. These tools also allow monitoring of pathogen abundance in asymptomatic carriers and the environment throughout the production cycle, which is critical for preventive health management under stressful summer conditions (Abdelsalam et al., 2022).

For large yellow croaker specifically, a duplex PCR assay targeting ompA genes of *Klebsiella pneumoniae* and Chryseobacterium enables simultaneous detection and discrimination of these emerging pathogens, which often produce similar clinical signs (Hu et al., 2024). The method detects as little as 20-200 fg genomic DNA or about 100 CFU, correctly identifies single and mixed infections in field samples, and is described as time-saving, specific, and convenient for epidemiological surveillance in aquaculture.

8.3 Construction of intelligent aquaculture and early warning systems

Modern disease control increasingly relies on integrated sensor and data-analytics platforms. Reviews of cutting-edge fish disease technologies highlight that IoT sensors, artificial intelligence, and machine-learning models can continuously track environmental parameters and fish activity, allowing farmers to predict disease outbreaks and intervene before large mortality occurs. Image-based systems using 2D/3D cameras under near-infrared light can capture swimming patterns and skin changes to detect early behavioral or external lesions, demonstrating practical noninvasive monitoring that can be embedded into early-warning workflows (Islam et al., 2024).

At the system level, IoT-ML architectures have proven capable of stabilizing water quality and reducing mortality in tropical aquaculture, even during high-temperature periods. One implementation using low-cost sensors to monitor temperature, dissolved oxygen, pH, and turbidity achieved extremely high predictive accuracy for water-quality parameters and enabled over 6000 automated corrective interventions, maintaining fish survival above 90% (Baena-Navarro et al., 2025). Complementary AIoT reviews describe how networks of sensors and cameras feeding AI models can jointly support water-quality prediction, disease recognition, and smart feeding, forming the backbone of intelligent aquaculture farms that can issue timely alerts and automate responses under rapidly changing thermal conditions.

9 Conclusions and Prospects

High-temperature seasons pose a central constraint on large yellow croaker aquaculture by narrowing the thermal safety window, redistributing energy away from growth, and increasing the risk of oxidative stress, hypoxia, and disease. Across systems, maintaining water temperature within the species' optimal range, ensuring sufficient dissolved oxygen, and avoiding sharp daily fluctuations emerged as the core environmental requirements for sustaining performance during summer. At the same time, evidence from ship-based offshore systems and improved cage designs shows that environmental risks can be substantially reduced through better site selection, mobility, and stratification management. Nutritional and health management strategies can further buffer thermal stress. Optimized protein-energy ratios, together with functional additives such as inulin and fulvic acid, support growth, stabilize metabolism, and reshape gut microbiota in favour of beneficial taxa under high summer temperatures.

Integrated multi-omics studies indicate that these diets enhance energy pathways while down-modulating excessive stress and inflammatory responses. In parallel, emerging breeding work on heat-tolerant and stress-resistant lines, along with gradually adopted intelligent monitoring and AI-supported decision tools, suggests that biological, nutritional, and technological approaches can be combined into a coherent health management framework for hot seasons.

Despite rapid progress, most experimental studies on large yellow croaker thermal stress are short-term, carried out under controlled or semi-controlled conditions, and focus on single factors such as temperature, diet, or transport. This limits understanding of how chronic multi-stressors—heat combined with hypoxia, pollutants, high density, and pathogens—interact over full production cycles. In addition, many multi-omics investigations are done at juvenile stages and in specific seasons, creating uncertainty about how findings scale to different life stages, strains, and farming regions. Methodologically, current work is often fragmented between physiology, nutrition, genetics, and engineering. Large, integrative field trials that compare different culture systems, diets, and management packages under realistic summer conditions remain scarce. Meanwhile, smart aquaculture and AI/AIoT research is dominated by generic models and laboratory or pilot demonstrations, with relatively few tools tailored to the behaviour, color, schooling patterns, and disease spectrum of large yellow croaker. Barriers such as high initial costs, requirement for technical expertise, and lack of standardized data pipelines also slow real-world deployment.

Future research should prioritize long-term, system-level studies that couple environmental regulation (temperature, oxygen, water quality) with precision nutrition, stocking-density control, and disease prevention for entire summer grow-out cycles. Combining multi-omics with continuous environmental and behaviour monitoring can clarify how specific management packages influence resilience, growth, and product quality. Parallel breeding and genomic selection programs targeting acute and chronic heat tolerance, hypoxia resistance, and disease robustness will be critical to create strains adapted to future warming. On the technological side, intelligent fish-farm concepts and AIoT platforms offer powerful prospects for high-temperature health management. Networked sensors, computer vision, and machine-learning models can underpin real-time control of feeding, aeration, and environmental alarms, while advanced diagnostic tools and AI-based disease recognition can support earlier, more targeted interventions. To make these solutions practical for croaker farmers, future work should emphasize species-specific model training, cost-effective modular hardware, explainable interfaces, and capacity building. Ultimately, integrating heat-tolerant germplasm, functional feeds, optimized offshore or recirculating systems, and intelligent management tools will be the key pathway to resilient, sustainable large yellow croaker aquaculture under a warming climate.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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