

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