

overall metabolic rates, while structure-related proteins were upregulated; this pattern indicates altered enzyme activity that reduces protein catabolism and redirects resources to growth under variable regimes. (Kang et al., 2019) Moderate heat stress in *H. rufescens* and *H. iris* also altered digestive enzyme profiles: in red abalone, maltase and aminopeptidases increased at high temperature, whereas in pāua, amylase and β -glucosidase decreased, but overall digestibility remained unchanged, indicating species-specific enzymatic adjustments that maintain nutrient acquisition under elevated demand (Frederick et al., 2022). Metabolomic studies reveal coordinated pathway shifts supporting thermal tolerance. In juvenile *H. discus hannai* acclimated at 10 °C versus 30 °C, acute exposure to 31 °C caused mitochondrial failure and accumulation of unstable intermediates, particularly in cold-acclimated animals, whereas warm-acclimated juveniles showed stronger capacity to produce beneficial metabolites, indicating enhanced regulation of mitochondrial amino-acid and fatty-acid oxidation (Xu et al., 2020). Under low-temperature stress, metabolomics of *H. discus hannai* show that differential metabolites are dominated by carbohydrates and that pathways such as carbohydrate digestion, starch/sucrose metabolism, TCA cycle and pyruvate metabolism are affected, suggesting that regulating carbohydrate use is central to energy supply and antifreeze protection in the cold (Li et al., 2024).

6.3 Gene expression and heat stress response mechanisms

At the molecular level, temperature stress elicits pronounced transcriptomic changes, particularly in genes linked to protein quality control and cellular protection. A meta-analysis of nine RNA-seq datasets across seven *Haliotis* species identified a core set of 74 heat-responsive genes enriched for heat shock proteins, ubiquitin-proteasome components, protein folding, and alternative splicing, indicating a conserved network that manages misfolded proteins and maintains proteostasis under heat stress (Barkan et al., 2025). Acute thermal exposure in *Pacific abalone* induces thousands of differentially expressed genes enriched in protein folding and endoplasmic-reticulum processing; numerous molecular chaperones are strongly upregulated, and ER-associated degradation pathways are activated, suggesting that maintaining ER homeostasis is central to surviving heat stress (Wu et al., 2023). Classical heat shock proteins show acclimation-dependent and rapid inducible responses. In *H. discus hannai*, long-term acclimation at 30 °C or 8 °C leads to elevated basal Hsp70 mRNA levels compared with 12 °C-20 °C, and the temperature that maximally induces Hsp70 during 30-min exposures is higher in warm-acclimated than cold-acclimated gills, demonstrating plastic shifts in induction thresholds. In *H. discus hannai* exposed to 26 °C-28 °C, survival declined and adhesion and foot structure were impaired, accompanied by increased antioxidant enzyme activities and significant upregulation of Hsp90, highlighting cascades from organismal performance to cellular defense as temperatures exceed 24 °C-26 °C.

7 Case Study: Impact of Seasonal Temperature Fluctuations in Intensive Abalone Farming Systems

7.1 Analysis of temperature variations and production performance in typical farming areas

Intensive abalone farming systems commonly experience pronounced seasonal and short-term thermal variability that shapes growth and production efficiency. In Australia, culture temperatures for hybrid abalone typically fluctuate between about 10 °C in winter and 25 °C in summer, far outside the reported thermal optima of ~17 °C-18 °C for parental species, and high summer mortality is recognized as a major constraint to economic performance (Hassan et al., 2023). Land-based systems with well-controlled temperature demonstrate that maintaining water in a stable, warm but sub-optimal range markedly improves predicted growth, confirming that temperature adjustment is a dominant driver of production performance in indoor cultures (Khiem et al., 2023). Field investigations in sea-based farms highlight how seasonal warming can progressively erode physiological condition. In Fujian, southern China, two-year-old *Pacific abalone* reared from April to October experienced a cumulative mortality of 58.58%, with seawater temperature showing a significant positive correlation with mortality and progressive depletion of protein, glycogen and non-esterified fatty acids toward late summer (Lin et al., 2017). At the same time, antioxidant indices (SOD, total antioxidative capacity) first increased and then declined in September and October, indicating that compensatory defense responses were eventually overwhelmed, with likely consequences for growth and harvest yields (Lin et al., 2017).