

Climate-model projections focused on northern large marine ecosystems further suggest that most future sea surface temperature change will arise from a positive shift in the mean, with only modest changes in variability, leading to a substantial increase in warm extremes and decrease in cold extremes; by late century, many regions are projected to be warmer every year than the warmest year of the late twentieth century (Alexander et al., 2018).

4 Effects of Temperature on Growth Performance of Abalone

4.1 Responses in growth rate and body weight gain

Growth performance in abalone shows a pronounced, often non-linear dependence on temperature. For *Haliotis midae* fed formulated diets, growth rate and feed consumption increase between 12 °C-20 °C, but both decline sharply from 20 °C-24 °C, with deterioration in protein efficiency ratio and feed conversion, indicating that temperatures above the natural range rapidly constrain weight gain (Morash and Alter, 2016). Size-dependent optima are also evident: juvenile *Haliotis iris* grow fastest at ~22 °C, whereas larger individuals peak at 17 °C-18 °C, suggesting that ideal grow-out temperatures decline as abalone increase in size (Steinarsson and Imsland, 2003; Searle et al., 2006). Integrated multitrophic aquaculture studies confirm that both size and temperature significantly shape specific growth rate (SGR) in *Haliotis discus hannai*. SGR follows a quadratic relationship with temperature within each size class, with small abalone (<15 g) performing best at 20 °C-22 °C and larger individuals at 15 °C-20 °C, underlining the need to tailor temperature regimes to body size for maximal body-weight gain (Fang et al., 2018). Long-term acclimation can also modify growth responses: domesticated *H. discus hannai* populations from warmer regions show enhanced thermal tolerance and improved capacity to redistribute energy under high temperatures, supporting better growth under warming conditions than naive northern stocks (Yu et al., 2023).

4.2 Changes in feeding behavior and digestive efficiency

Feeding behaviour and ration size are strongly temperature dependent. In *H. midae*, daily food intake rises from about 8.1% of wet flesh mass at 14 °C to 11.4% at 19 °C, indicating higher consumption at warmer temperatures, while a clear nocturnal feeding rhythm (16:00-08:00) supports nighttime grazing as temperatures and activity peak. In green abalone *Haliotis fulgens*, feed consumption increases at night and is higher at 25 °C than at 20 °C across photoperiods, yet growth and survival decline at 25 °C, suggesting that elevated intake cannot fully offset thermal stress and reduced conversion efficiency. Temperature also influences digestive efficiency and enzyme activity. Moderate heat stress (5 °C above ambient for six weeks) elevates metabolic rates in *Haliotis rufescens* and *H. iris*, but apparent digestibility of organic matter, protein and carbohydrate remains unchanged, indicating that digestive efficiency can be maintained despite higher energetic demand (Frederick et al., 2022). In post-weaned greenlip abalone, raising temperature from 14 °C to 20 °C significantly increases trypsin, amylase and lipase activities, and improves feed conversion at 20 °C, suggesting that warmer conditions within the optimal range enhance enzymatic capacity and nutrient utilization (Bansemer et al., 2023).

4.3 Impacts on shell formation and energy allocation

Temperature affects shell formation both through calcification rates and through molecular pathways of biomineralization. In *Haliotis tuberculata*, calcification rates are lower in cool seasons and higher in warmer seasons, paralleling temperature-driven changes in respiration and excretion and indicating increased shell deposition when thermal and metabolic conditions are favourable (Chappon et al., 2018). Under combined warming and acidification, however, reconstructed shells of *H. discus hannai* develop corroded and irregular aragonite plate microstructures, and key nacre protein genes (Hdh-AP7, Hdh-AP24) that induce crystal formation become highly sensitive to thermal stress, demonstrating direct damage to shell quality through disturbed expression of biomineralization genes. (Zheng et al., 2020). Energy allocation under thermal variation reflects a balance between maintenance, growth and shell production. In *H. discus hannai* cultured in an abalone-kelp IMTA system, all measures of carbon allocation (including respiration, excretion and growth carbon) increase with temperature, and optimum regimes are size-specific, implying that higher temperatures drive greater overall energy throughput but require careful matching of food supply to sustain shell and tissue growth (Fang et al., 2018). Physiological studies under fluctuating and high summer temperatures show that elevated metabolic and ammonia excretion rates at warm conditions can deplete tissue energy reserves when food intake does not keep pace, leading to disturbed maintenance and reduced growth, which likely includes compromised shell deposition (Kang et al., 2019).