of temperature variation-such as chronic warming, short heatwaves, or diel fluctuations-affect growth trajectories and survival across life stages and genotypes.

The present study therefore aims to quantify how realistic temperature variation regimes influence growth and survival of farmed abalone, and to relate observed performance to putative stress thresholds identified in previous physiological and omics studies (Chen et al., 2016). It is hypothesized that moderate fluctuations around sub-lethal means will support better growth and survival than sustained exposure near upper tolerance limits, and that these responses will provide practical guidance for temperature management, selective breeding, and site selection in abalone farming under climate change (Xu et al., 2020).

2 Biological and Ecological Characteristics of Abalone Related to Temperature Response

2.1 Physiological characteristics and growth/development patterns of abalone

Abalone are poikilothermic, so temperature strongly shapes growth trajectories and optimal size-at-age in culture and the wild. In integrated abalone-kelp systems, specific growth rate of *Haliotis discus hannai* shows a clear quadratic relationship with temperature in each size class, and optimal culture temperatures differ for small (<15 g) versus larger (>15 g) individuals, indicating size-dependent thermal optima for growth (Fang et al., 2018). Experimental work on Australian hybrid abalone similarly shows that growth, weight gain and shell extension all increase from 12 °C to 22 °C, confirming that warmer conditions within the tolerable range enhance growth performance during the grow-out phase (Hassan et al., 2023). Temperature effects on development also act indirectly through food quality and nutrition. For juvenile red abalone, growth and condition are significantly better when fed dulse cultured at higher temperatures, because warmer-grown seaweed has higher protein and nitrogen content, linking primary producer thermal responses to abalone growth potential (Rizzo et al., 2024). At larger spatial scales, physiological thermal optima for scope for growth around 24 °C, with an upper limit near 30 °C, help explain observed distribution patterns of wild abalone along thermal gradients (Lluch-Cota et al., 2023).

2.2 Respiratory metabolism and energy allocation mechanisms

Temperature directly modulates respiratory metabolism in abalone, altering oxygen consumption, excretion and substrate use. In *Haliotis discus hannai* exposed to semidiurnal temperature fluctuations between 20 °C-26 °C, metabolic rate tracks short-term temperature changes and rises sharply under stable warm conditions, while similar ammonia excretion across treatments indicates that elevated energy demands are partly met by protein catabolism (Kang et al., 2019). Similarly, cold-acclimated *Haliotis midae* show increased oxygen consumption and nitrogen excretion during acute warming, reflecting greater reliance on proteins as metabolic fuel under short-term thermal stress. With longer-term thermal exposure, abalone can adjust energy allocation among metabolic pathways. After a month at elevated temperatures, *H. midae* partially compensate by reducing mass-specific oxygen and nitrogen fluxes and shifting towards carbohydrate use at 22 °C, indicating acclimatory changes in fuel selection. Metabolomic and transcriptomic studies in juvenile and hybrid abalones under heat stress show coordinated activation of aerobic pathways (TCA cycle, oxidative phosphorylation) alongside anaerobic glycolysis, supporting ATP production when oxygen demand rises and solubility drops at high temperatures (Xu et al., 2020).

2.3 Thermal tolerance ranges and ecological distribution characteristics

Thermal tolerance in abalone is often quantified using critical temperatures or cardiac performance thresholds, revealing interspecific and hybrid differences. In *Haliotis discus hannai*, *H. gigantea* and their hybrid, Arrhenius break temperatures of cardiac performance, as well as lethal limits and critical thermal maxima, are highest in the hybrid (≈32.5 °C), intermediate in *H. gigantea*, and lowest in *H. discus hannai*, indicating enhanced tolerance and suggesting that warming will differentially impact these taxa in culture (Chen et al., 2016). Size-dependent analyses in Australian hybrid abalone show that, under slower, ecologically realistic warming, larger individuals have lower critical thermal maxima, implying that marine heatwaves and chronic warming may preferentially favour smaller, less fecund animals in farms and wild populations (Holland et al., 2023). At population and species scales, acclimation history and oxygen availability further modulate realized thermal niches and distribution. Work integrating scope for growth with sea-surface temperature shows that wild abalone densities off Baja California are