but also as a multifunctional system with relevance to food security, circular bioeconomy development, and coastal sustainability transitions (Ross et al., 2023).

However, the same climate pressures that elevate the strategic value of kelp farming also expose serious vulnerabilities across the production cycle. Ocean warming can reduce biomass yield, alter biochemical composition, and impair reproduction, while marine heatwaves, storms, disease outbreaks, and herbivory create episodic but sometimes severe losses for farms and nurseries (Veenhof et al., 2024). These risks are compounded by declining germplasm quality, genetic contamination between cultivated and wild stocks, and uncertainty about how multiple stressors interact across microscopic and macroscopic life stages. Evidence from kelp-focused syntheses shows that warming has broadly negative effects on growth, reproduction, and survival across life stages, whereas responses to acidification alone are often weaker or more variable; importantly, combined warming and acidification can act synergistically, and impacts tend to intensify with stronger or longer exposure (Roethler et al., 2025). For the kelp aquaculture industry, this means that climate change threatens not only farm productivity, but also the biological reliability of seedstock, seasonal scheduling, and the spatial suitability of traditional cultivation grounds.

These challenges make adaptation research a central requirement for the future of kelp aquaculture rather than a secondary management option. Recent literature points to several promising directions, including future-proof site selection, development of stress-resistant cultivars, selective breeding informed by thermal tolerance and genetic diversity, microbiome-based resilience strategies, and cultivation models that integrate production with restoration or broader ecosystem management (Hu et al., 2021; Veenhof et al., 2024). Experimental work further suggests that heat-tolerant genotypes can perform better under warm farming conditions, although preserving broader genetic diversity remains essential for long-term adaptability (Harden et al., 2024). At the same time, integrated planning that accounts for climate exposure, stakeholder conflicts, and ecosystem carrying capacity is needed to avoid maladaptation and sustain both livelihoods and surrounding coastal ecosystems. Accordingly, studying adaptation strategies for kelp farming under climate change is significant not only for safeguarding yields, but also for supporting resilient coastal economies, maintaining ecosystem services, and enabling kelp aquaculture to contribute credibly to sustainable development under rapidly changing ocean conditions.

2 Mechanisms of Climate Change Impacts on Kelp Aquaculture

2.1 Effects of rising seawater temperatures on kelp growth and development

Rising seawater temperature directly constrains kelp growth because kelp performance is strongly temperature dependent, with reduced growth above species-specific optima and lower net energy gain when respiration rises faster than photosynthesis (Simonson et al., 2015). Across a global synthesis of 143 experimental studies, ocean warming showed a consistently negative effect on kelps at all life stages, impairing growth, reproduction, and survival, which indicates that warming is not a narrow local problem but a general mechanism of production risk for kelp aquaculture (Roethler et al., 2025). For farms, this means that elevated background temperatures can depress biomass accumulation over an entire production cycle while also making crop performance more sensitive to exposure intensity and duration.

Thermal stress also acts through damage to tissue integrity and early development, thereby reducing both standing biomass and recruitment success. In juvenile *Macrocystis pyrifera*, simulated marine heatwaves reduced mean growth rates by more than 30% even at moderate heatwave intensities, while 22°C caused bleaching, blade erosion, reduced chlorophyll fluorescence, and mortality (Bunting et al., 2024). Microscopic stages are especially vulnerable: in bull kelp, gametophyte densities declined sharply at 18°C, 20-22°C was lethal, and sporophyte production was greatly reduced at 16°C-18°C, narrowing the temperature window for successful recruitment.

2.2 Effects of ocean acidification on physiological metabolism and quality formation

Ocean acidification affects kelp mainly through altered carbon chemistry, but its biological consequences are more variable than those of warming because many kelps can use bicarbonate efficiently through carbon-concentrating mechanisms. In *Macrocystis pyrifera*, elevated pCO_2 and reduced pH did not change growth or photosynthetic rates over a 7-day incubation, and this stability was linked to continued reliance on HCO3- uptake and sustained carbonic