anhydrase activity (Fernández et al., 2015). A recent global meta-analysis similarly found that ocean acidification generally had no overall effect on kelps except for a negative effect on reproduction, indicating that physiological metabolism in farmed kelps may often remain comparatively stable under acidification alone, while reproductive output remains a key vulnerability (Roethler et al., 2025).

Even so, acidification can still influence quality formation indirectly by modifying photosynthesis-respiration dynamics and by interacting with diel pH variability or other climate drivers. In *Ecklonia radiata*, pH fluctuations enhanced juvenile growth and photosynthesis under present-day mean pH, but this advantage disappeared or reversed when mean pH was reduced by 0.3 units, suggesting that future acidification may erode favorable local carbonate dynamics that currently support productivity (Britton et al., 2016). More broadly, responses of marine photosynthetic organisms to acidification depend on concurrent warming, light, nutrient supply, and oxygen conditions, and combined stressors can be synergistic, neutral, or antagonistic, which means kelp quality traits should not be interpreted from acidification-only experiments in isolation.

2.3 Effects of extreme weather events on aquaculture system stability

Extreme weather events affect kelp aquaculture not only biologically but mechanically, because farms depend on ropes, rafts, anchors, and other structures that remain exposed to waves, surge, and rapid hydrodynamic forcing. Aquaculture in general is inherently vulnerable to climate change because it relies heavily on the ambient environment, and major climate-related stressors include extreme weather, surge-based flooding, and shifts in temperature, salinity, and dissolved oxygen. The severity of impact depends on where the stress falls relative to tolerance limits, its duration over the production cycle, and the interaction of multiple simultaneous stressors, so identical storm events can produce very different outcomes across farms, species, and life stages.

For exposed marine systems, storm waves are a direct pathway to infrastructure failure and crop loss. Quantitative risk assessment in the northern East China Sea showed that tropical cyclone-induced extreme waves can destabilize aquaculture structures and generate spatially concentrated high-risk zones, underscoring the need for wave-resilient farm design and hazard mapping (Fang et al., 2025). Empirical evidence from other aquaculture sectors points in the same direction: in Türkiye, storms and flash floods accounted for 56.5% of escape incidents, while in coastal Vietnam floods and typhoons caused measurable losses of income and initial investment, demonstrating that extreme events can rapidly convert climate exposure into operational and economic instability (Lam et al., 2024; Bal and Dürrani, 2025).

3 Physiological and Ecological Responses of Kelp to Climate Change

3.1 Changes in photosynthesis and carbon fixation capacity

Ocean warming generally depresses kelp photosynthetic performance and carbon fixation, while ocean acidification alone often provides little compensation. A global meta-analysis across 143 experimental studies found that warming negatively affects kelps across life stages and physiological functions, whereas acidification usually has no effect except on reproduction (Roethler et al., 2025). Species-level experiments are consistent with this pattern: in *Ecklonia radiata*, elevated CO_2 increased photosynthesis near the thermal optimum but did not improve growth, indicating that additional dissolved CO_2 is unlikely to offset warming-induced performance losses (Britton et al., 2024).

The consequences extend from individual physiology to ecosystem carbon cycling. Along a natural temperature gradient in NE Atlantic Laminaria hyperborea forests, kelp in warm regimes assimilated more than three times less carbon and exported less than half as much particulate carbon as kelp in colder regimes, implying substantial climate-driven weakening of blue-carbon function (Pessarrodona et al., 2018). Community reorganization further amplifies this loss: marine heatwaves favor shifts from canopy-forming kelps to turf assemblages, and such structural change reduces long-term carbon sequestration potential in coastal systems (Gao et al., 2021).

3.2 Regulatory mechanisms for nutrient uptake and energy allocation

Climate change alters nutrient regulation by disrupting the tight coupling between carbon metabolism, nitrogen assimilation, and growth. In *Macrocystis pyrifera*, nitrate availability modulated thermal plasticity, buffering the