negative effects of high temperature on growth and photosynthesis during short-term exposure, which indicates that nutrient status directly regulates acclimatory capacity under warming (Fernández et al., 2020). However, this buffering has limits, because supra-optimal warming can override nutritional benefits and produce metabolic stress even when nitrogen is available (Fernández et al., 2020; Fales et al., 2023).

Recent studies also show that nitrogen and phosphorus pathways respond differently to warming, revealing important trade-offs in energy allocation. In juvenile *Saccharina latissima*, nitrate uptake declined significantly at and above 15.7°C, whereas phosphate uptake remained positive across most treatments and even became decoupled from nitrate behavior at high temperature, suggesting distinct regulatory mechanisms for N and P metabolism (Ding et al., 2025). Under phosphorus deficiency combined with thermal and high-light stress, cultivated *Saccharina japonica* first suppressed metabolism to conserve resources, then activated energy, amino acid, and coenzyme pathways under compound stress, showing a shift from metabolic conservation to compensatory energy mobilization (Zhang et al., 2025).

3.3 Changes in stress resistance and environmental adaptability

Kelp stress resistance under climate change depends on both immediate physiological tolerance and the capacity for recovery after extreme events. In juvenile *Macrocystis pyrifera*, short marine heatwave exposure caused oxidative damage, reduced growth, and lowered photosynthetic capacity, but removal of the heat stress allowed partial physiological recovery, indicating some short-term resilience (Umanzor et al., 2021). Even so, when warming coincided with nitrate scarcity, damage to photosynthetic capacity became irreversible, highlighting that multiple stressors sharply reduce recovery potential (Umanzor et al., 2021).

Environmental adaptability also varies strongly among populations and species, implying that climate responses cannot be generalized across farming regions or target taxa. Genomic analysis of *Ecklonia radiata* revealed adaptive variation linked to temperature and light, but also predicted substantial future genotype-environment mismatch under climate change, suggesting that natural adaptation may not keep pace with warming. At the same time, experiments on Arctic kelp communities found comparatively high tolerance to short-term warming and marine heatwaves, although some species still showed reduced quantum yield or net photosynthesis, demonstrating that resilience is real but species-specific rather than universal (Lebrun et al., 2025).

4 Key Technical Strategies for Climate Change Adaptation in Kelp Aquaculture

4.1 Breeding of new heat-tolerant and stress-resistant varieties

Breeding heat-tolerant and stress-resistant kelp varieties is a primary adaptation strategy because warming has strong negative effects on kelp growth, reproduction, and survival across life stages, while tolerance varies substantially among genotypes and populations (Alsuwaiyan et al., 2021; Roethler et al., 2025). Early life-stage experiments in *Ecklonia radiata* further show significant genotype-by-environment interactions under marine heatwave conditions, indicating that some genotypes are consistently more resistant and could be used as broodstock for selective breeding (Alsuwaiyan et al., 2021).

Population-level variation also supports targeted breeding for aquaculture resilience. In *Macrocystis pyrifera*, geographically isolated populations differ in thermal tolerance and nitrogen storage capacity, showing that locally adapted physiological traits already exist within cultivated or cultivable kelp germplasm (Fernández et al., 2020). However, breeding solely for heat tolerance can narrow adaptive potential, so improvement programs should combine resistant genotypes with broader genetic diversity to preserve long-term resilience under variable future stressors (Alsuwaiyan et al., 2021).

4.2 Optimization of farming zones and spatial layout adjustments

Climate adaptation also depends on moving cultivation toward locations where thermal, light, and nutrient conditions remain within kelp performance windows. Warm climatic regimes in the NE Atlantic support more than threefold less carbon assimilation and less than half the particulate carbon donation of cold regimes, indicating that site temperature strongly shapes kelp productivity and should guide farming-zone selection. At smaller scales,