increased turbidity can reduce kelp productivity by 95%, so spatial layout must account not only for temperature but also for water clarity and light penetration (Blain et al., 2021).

Spatial adjustment within farms can also buffer compound stress. Experiments on northeast Atlantic kelps showed that summertime marine heatwaves caused major declines in biomass and photosynthetic efficiency under low light, whereas the same species were largely resistant under high-light conditions, suggesting that layout choices affecting depth, shading, and water clarity can materially alter resilience. Because kelp responses vary across populations and environments, farming zones should be matched to locally appropriate genotypes rather than assuming uniform performance across regions (Fales et al., 2023).

4.3 Intelligent monitoring and precision aquaculture management technologies

Intelligent monitoring is increasingly necessary because kelp responses to climate change depend on multiple interacting stressors rather than temperature alone. Recent work on cultivated *Saccharina japonica* identifies major knowledge gaps in tolerance thresholds, metabolic trade-offs, and compensatory acclimation under combined stressors, and explicitly proposes real-time monitoring systems and machine-learning forecasting as adaptation tools for kelp aquaculture (Zhang et al., 2025). Precision fertilization is another recommended approach, because nutrient optimization can reduce deficiency stress without worsening eutrophication risk (Zhang et al., 2025).

Precision management is especially important because nutrient and temperature effects interact in complex ways. In juvenile *Saccharina latissima*, nitrate uptake declines sharply at or above 15.7°C and can shift to nitrate release at high temperatures, while phosphate uptake remains positive, showing that warming disrupts nutrient regulation in ways that require continuous monitoring rather than static farm schedules (Ding et al., 2025). Short-term experiments in *Nereocystis luetkeana* and *Saccharina latissima* likewise show that elevated temperature reduces growth and causes metabolic stress even when nitrogen is available, reinforcing the need for integrated sensor-based management of heat and nutrient conditions during cultivation (Figure 1) (Fales et al., 2023).

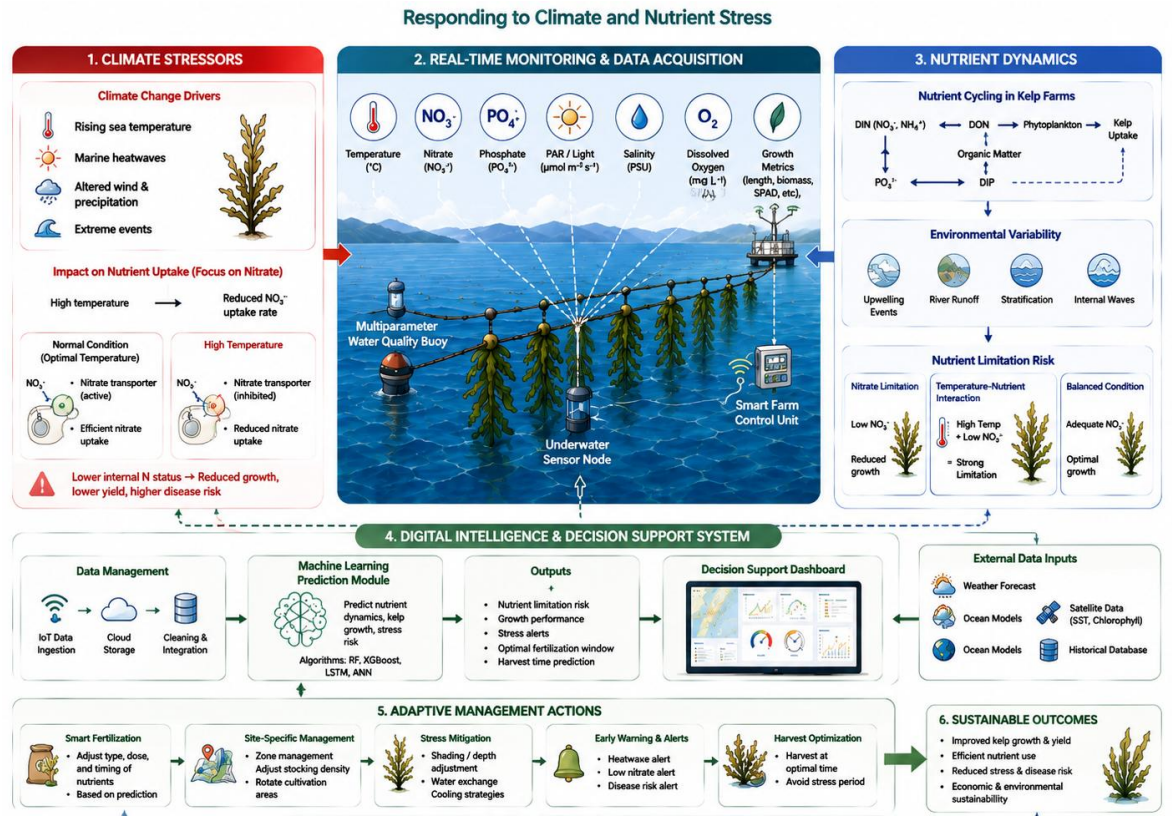

Figure 1 Integrated smart monitoring and decision-support framework for kelp (*Saccharina* spp.) aquaculture under combined climate and nutrient stressors