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Adaptation Strategies for Kelp Farming Under Climate Change

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Abstract Climate change is increasingly challenging the sustainability and productivity of kelp farming through ocean warming, marine heatwaves, ocean acidification, extreme weather events, and shifts in nutrient availability. This paper systematically reviews adaptation strategies for enhancing the resilience of kelp farming under changing marine environmental conditions. It first examines the physiological, genetic, and ecological responses of kelp to major climate stressors, with particular emphasis on thermal tolerance, photosynthetic regulation, oxidative stress, genetic diversity, and ecological interactions. The paper then evaluates adaptive cultivation and farm management strategies, including optimized site selection, seasonal production adjustment, cultivation-depth regulation, stocking-density management, and environmental monitoring. Biological and technological approaches, such as selective breeding, controlled hatchery production, genomics, transcriptomics, and microbiome-based research, are further discussed for developing climate-resilient kelp strains. Integrated multi-trophic aquaculture and climate-smart management are highlighted as ecosystem-based approaches for improving resource-use efficiency and reducing production risks. A representative case study is proposed to evaluate the practical implementation and effectiveness of regional adaptation measures. Finally, the integration of artificial intelligence, remote sensing, predictive modeling, and digital monitoring is discussed as an important pathway toward intelligent and climate-resilient kelp aquaculture.
Keywords Kelp farming; Climate change; Climate adaptation; Thermal stress; Sustainable aquaculture

1 Introduction

Anthropogenic climate change is reshaping the marine environment through rising atmospheric CO_2, ocean warming, acidification, altered salinity regimes, and more frequent extreme events. Atmospheric CO_2 has increased from about 280 ppm in the pre-industrial era to 420 ppm, and much of the resulting excess heat has been absorbed by the ocean, driving persistent changes in sea temperature and seawater chemistry (Veenhof et al., 2024). These changes are especially consequential for kelps because their physiology, reproduction, and geographic distribution are tightly linked to temperature and other environmental controls. Across temperate and polar systems, warming trends and marine heatwaves are associated with reduced kelp growth and survival, disrupted recruitment, and poleward shifts or contractions at warm range edges, while interacting stressors such as sedimentation, deoxygenation, and freshwater inputs can intensify local impacts. As a result, climate change is no longer a distant background pressure for kelp cultivation but an immediate oceanographic reality that is redefining where, when, and how kelp can be farmed successfully (Roethler et al., 2025).

Against this environmental backdrop, kelp aquaculture has become one of the most important sectors of global marine biomass production and a strategically valuable component of the blue economy. Seaweed aquaculture accounts for more than half of global mariculture production and continues to expand, while cultivated kelps such as *Saccharina japonica* and *Undaria pinnatifida* remain among the most economically important macroalgal crops worldwide (Duarte et al., 2021; Hu et al., 2021). In production terms, kelp farming is still concentrated overwhelmingly in Asia, especially China, where industrial-scale cultivation has shaped global supply, technology development, and germplasm resources. Beyond its role as a food and hydrocolloid feedstock, kelp farming is increasingly valued for broader ecosystem services and industrial applications, including nutrient removal, habitat provision, carbon uptake, and use in bioenergy and biorefinery pathways. This combination of commercial output and ecological co-benefits explains why kelp cultivation is now widely viewed not only as an aquaculture activity, 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 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 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, 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).

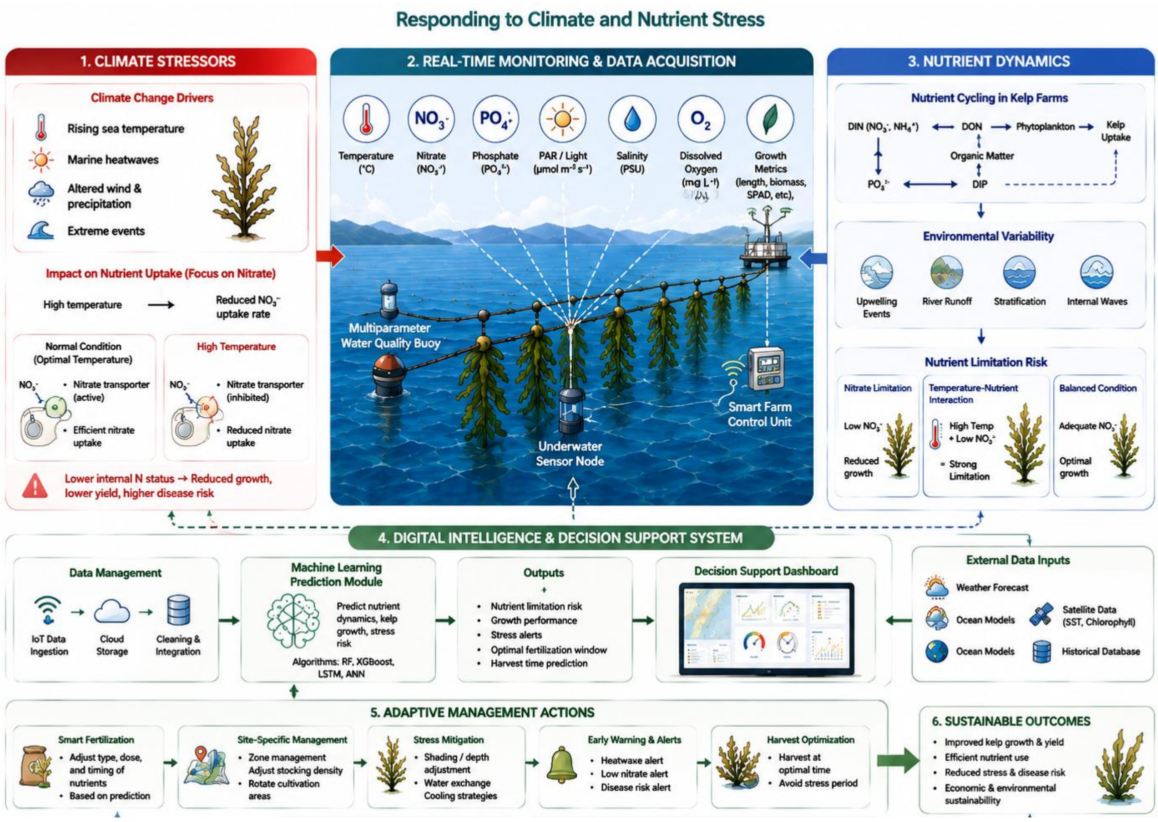

Figure 1 Integrated smart monitoring and decision-support framework for kelp (*Saccharina* spp.) aquaculture under combined climate and nutrient stressors

5 Ecological Adaptation and Integrated Management Strategies for Kelp Aquaculture

5.1 Establishment of multi-trophic integrated aquaculture models

Integrated multi-trophic aquaculture (IMTA) is a core ecological adaptation strategy for kelp farming because it couples kelp with fed or extractive species to recycle dissolved and particulate wastes, thereby improving the environmental performance of aquaculture systems under climate stress (Troell et al., 2009). Reviews of IMTA consistently describe seaweed, especially kelp, as the inorganic extractive component that can increase sustainability by converting nutrient effluents into additional biomass and co-products rather than allowing those nutrients to accumulate locally (Zhu et al., 2025).

For kelp aquaculture, the practical value of IMTA lies in both biogeochemical buffering and production diversification. In land-based integrated systems, seaweed raised mean seawater pH by 0.2 units and improved juvenile abalone growth by 22% in weight and 11% in shell area, showing that macroalgae can partially buffer acidification stress for co-cultured species (Hamilton et al., 2022). At larger commercial scales, Sanggou Bay demonstrates that IMTA can operate across whole coastal landscapes, with more than 30 species and over 240,000 t of annual seafood production, although adaptive management still depends on better understanding interactions among species, nutrient cycling, and surrounding environmental conditions.

5.2 Ecological restoration and environmental regulation measures

Ecological adaptation in kelp aquaculture should extend beyond farm production to the restoration and protection of surrounding kelp ecosystems, because farmed kelp does not reliably replace the biodiversity functions of natural kelp forests. Evidence to date indicates that kelp farms can create structured habitat and support distinct assemblages, but they typically form novel habitats rather than ecological equivalents of wild kelp forests (Forbes et al., 2022). This makes restoration and conservation of natural kelp habitats a parallel priority, especially as kelp forests are declining globally and their loss reduces biodiversity, primary production, nutrient cycling, and other ecosystem services.

Environmental regulation measures should therefore combine nutrient management, preventive conservation, and ecosystem-based governance. Field evidence from eutrophic Xiangshan Bay showed that kelp cultivation reduced dissolved inorganic nitrogen and phosphorus and removed an estimated 297 t of nitrogen and 42 t of phosphorus annually through harvest, confirming its utility as a bioremediation tool when deployed at appropriate scale (Jiang et al., 2020). At the same time, kelp ecosystem management is most effective when it follows ecosystem-based principles such as biologically relevant monitoring, cumulative-impact assessment, cross-scale governance, rapid adaptive management, and protection of food-web structure (Hamilton et al., 2022).

5.3 Risk early-warning and disaster emergency management systems

Risk early-warning systems are a necessary adaptation measure because climate change is increasing exposure to heatwaves, storms, low-oxygen events, and disease risks across aquaculture sectors. Climate risk assessment frameworks for aquaculture already identify temperature sensitivity, flooding and storm surge exposure, low-oxygen hazard, and disease vulnerability as major risk dimensions that can be evaluated in advance to support targeted adaptation planning. For kelp aquaculture, this implies that farm management should move from reactive loss response toward routine hazard mapping, threshold setting, and preparedness planning tied to local environmental drivers (Masanja et al., 2024).

Operationally, effective warning systems depend on integrating forecasts with local sensor observations and clear communication pathways. Recent aquaculture applications show that model-sensor systems can forecast farm water temperature up to 120 h ahead with errors below 2°C for up to 72 h, enabling precautionary measures before extreme temperature damage occurs (Li et al., 2024). IoT- and AI-based warning platforms have also predicted water-quality conditions 72 h in advance with 91.22% accuracy and delivered alerts through web and SMS interfaces, suggesting a practical template for kelp farming emergency systems that link monitoring, rapid communication, and farm-level response actions.

6 Case Study: Climate Adaptation Practices in Typical Kelp Farming Regions

6.1 Overview of the case study region and climate change characteristics

China, especially its northern production centers such as Shandong and Liaoning, remains the world's largest kelp farming region and therefore offers the clearest case for examining climate adaptation in commercial cultivation. At the same time, newer farming regions in the North Atlantic, such as Maine and Scandinavia, are increasingly important because they combine rapid industry expansion with strong exposure to changing coastal conditions. Across these regions, warming, shifting seasonality, and growing environmental variability are now central constraints on farm productivity and planning (Hu et al., 2021).

Climate risk is not limited to gradual warming. Evidence from China shows that *Saccharina japonica* is already among the most thermally sensitive cultivated macroalgae, and projected warming under future emissions scenarios is expected to increase heat stress across many aquaculture zones. Broader synthesis across kelp systems also shows that ocean warming reduces kelp growth, reproduction, and survival across life stages, while combined warming and acidification often intensify these effects (Roethler et al., 2025).

In practice, climate impacts also emerge through indirect and region-specific pathways. In Sanggou Bay, anomalous environmental change was linked to microbiome disruption and disease outbreaks in farmed kelp, indicating that climate stress can amplify biological hazards rather than acting only through physiology. On Canada's Pacific coast, marine heatwaves advanced bryozoan outbreaks on giant kelp, showing that warming can shift the timing and severity of epibiotic pressure in ways relevant to harvest scheduling and site choice (Zhang et al., 2024; Denley et al., 2025).

High-latitude and offshore-facing regions are not insulated from these threats. Reviews from the northeast Pacific indicate that future kelp performance will be shaped not only by temperature, but also by salinity, sediment load, and light, with important gaps remaining for vulnerable microscopic stages. More generally, ocean warming has already altered the structure and distribution of kelp ecosystems in many parts of the world, even though some populations remain locally stable over decadal scales (Smale, 2019; Drakard et al., 2023).

6.2 Implementation process of adaptation strategies and key technical measures

Adaptation in kelp farming generally begins with risk recognition, followed by adjustments in siting, seedstock, farm design, and seasonal operations. In China, proposed responses to climate pressure include preserving wild and cultivated germplasm, selecting sites suited to changing environmental conditions, breeding stress-resistant cultivars, and adopting innovative cultivation models. Similar ecosystem-based guidance from Europe and North America emphasizes climate resilience, protection of wild genetic diversity, and management systems that account for environmental carrying capacity (Hu et al., 2021).

Site selection is a first-line adaptation because local exposure strongly shapes farm vulnerability. Chinese reviews identify the selection of suitable cultivation sites under changing conditions, including possible expansion into more offshore spaces, as a major response to warming and other coastal pressures. Canadian case evidence similarly shows that adaptive management can favor cooler and more wave-exposed sites, while reducing harvests in warmer years and shifting harvest earlier when seasonal warming arrives unusually soon (Hu et al., 2021; Denley et al., 2025).

A second implementation pathway is biological improvement of farm stock. Recent experimental work suggests that thermal priming of *Saccharina latissima* gametophytes can increase subsequent sporophyte growth by up to 30% and extend tolerance under heat stress, indicating a practical crop enhancement route for warming seas. Genomic work on southern Chinese *S. japonica* cultivars further indicates that adaptation to relatively high seawater temperature involves changes in amino acid metabolism, sugar metabolism, osmotic regulation, and innate immune responses, supporting selective breeding for thermal resilience (Figure 2).

A third pathway is engineering adaptation. Because sheltered nearshore space is limited, offshore cultivation is increasingly proposed as a climate adaptation option, but it requires more robust infrastructure. Engineering analyses show that offshore systems must withstand strong waves, currents, and wind, and that mooring-line cost is a dominant determinant of capital expenditure, so technical adaptation depends not only on biological feasibility but also on structural reliability and economic design (Hu et al., 2021; Lian et al., 2024).

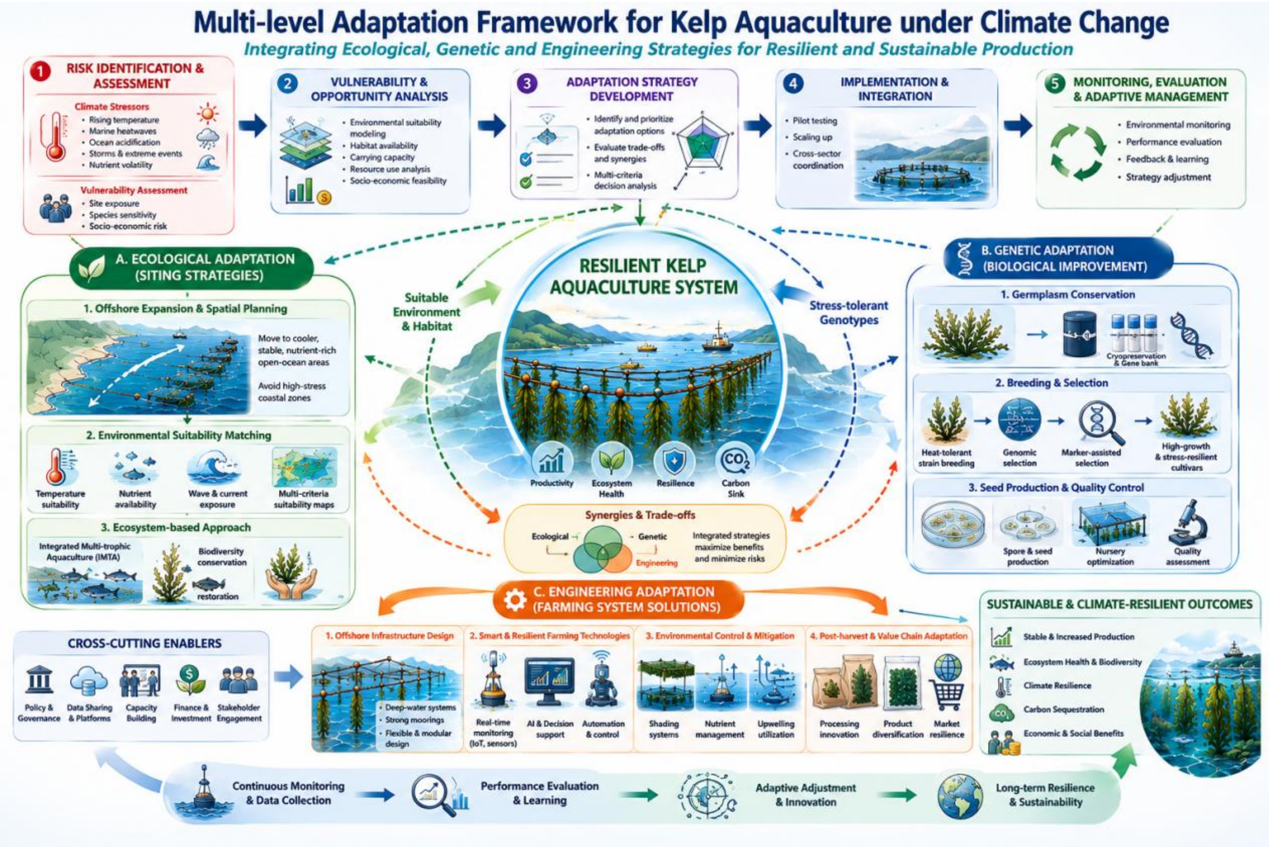

Figure 2 Multi-level adaptation framework for kelp aquaculture under climate change integrating ecological, genetic, and engineering-based strategies

6.3 Evaluation of ecological, economic, and social benefits

The ecological benefits of adaptation are strongest when strategies maintain production while also reducing environmental pressure in coastal waters. In China, kelp cultivation has already been estimated to remove substantial amounts of nitrogen and phosphate, assimilate large quantities of CO_2, and release oxygen, indicating that climate-resilient kelp farming can support nutrient management and carbon-related ecosystem services when farms remain productive. At broader scales, kelp systems generate major ecosystem-service value through fisheries support, nutrient cycling, and carbon removal (Hu et al., 2021).

These benefits, however, should not be overstated. Farm-scale evidence from Rhode Island found that a small sugar kelp farm produced negligible local ocean-acidification mitigation over a full growing season, with signals small relative to natural variability. Reviews of kelp farm biodiversity similarly conclude that farms can provide habitat and some ecosystem services, but they usually create novel communities rather than functioning as ecological equivalents of natural kelp forests (Forbes et al., 2022).

Economic gains from adaptation depend on both output stability and production efficiency. A life-cycle assessment of a 400-hectare Chinese kelp farm found relatively low climate impacts per ton of fresh kelp compared with smaller evaluated systems, while identifying plastics and buoys as key hotspots and recycling as the most effective improvement measure. In Europe, socioeconomic assessment from Sweden suggests that large-scale kelp farming can become profitable, but that biomass market value, rather than nutrient-removal payments alone, is likely to drive industry expansion (Hasselström et al., 2020; Li et al., 2023).

Social benefits are most evident where adaptation is embedded in local governance and livelihood systems. Maine's experience shows that kelp farming can diversify coastal economies and is often valued partly for ecological and ethical production practices, while broader ecosystem-approach work links the sector to alternative livelihoods and community well-being. On Canada's Pacific coast, co-designed monitoring with Indigenous stewardship organizations shows that adaptation can also strengthen social-ecological resilience by aligning harvest decisions with local knowledge, climate signals, and community priorities (Denley et al., 2025).

Across typical kelp farming regions, climate adaptation is most effective when it combines site selection, resilient seedstock, engineering upgrades, and participatory management. The evidence supports real ecological, economic, and social gains, but it also shows that benefits are context-dependent and strongest when claims remain aligned with measured outcomes.

7 Issues and Challenges in Climate Change Adaptation for Kelp Aquaculture

Climate change adaptation in kelp aquaculture is constrained not only by the direct effects of warming, acidification, storms, and disease, but also by uncertainty over how these stressors will interact across locations, species, and farming stages (Veenhof et al., 2024; Yadav et al., 2024). These uncertainties complicate decisions on site selection, breeding priorities, farm design, harvest timing, and investment planning, especially in emerging farming regions where long-term operational experience remains limited (Coleman et al., 2022; Veenhof et al., 2024).

At the same time, adaptation is not simply a technical problem. Its success depends on whether farmers can access affordable technologies, whether new systems are economically viable at commercial scale, and whether governance frameworks are flexible enough to support forward-looking responses rather than reactive coping. For kelp aquaculture, the major challenges therefore lie in managing climate uncertainty, overcoming technological and financial barriers, and building policy systems that can enable planned adaptation over long time horizons (Veenhof et al., 2024).

7.1 Risks associated with climate change uncertainties

A central challenge for kelp farming is that future climate exposure is difficult to predict with sufficient local precision for operational decisions. Ocean warming, acidification, altered seasonality, and extreme events can reduce kelp biomass, shift biochemical composition, and damage farms, but their intensity and timing vary across regions and years (Veenhof et al., 2024). More broadly, aquaculture adaptation depends on projections that are accurate enough to guide producers, because unrealistic or biased estimates of climate risk can mislead both farmers and policymakers and increase the risk of maladaptation (Maulu et al., 2021).

Uncertainty is amplified because multiple stressors often act together, while the evidence base remains uneven across stressor types and life stages. High-latitude kelps are projected to face range contractions, with risks intensified by marine heatwaves and increased freshwater and sediment inputs, yet important gaps remain in understanding how kelp microstages respond to combined stressors (Drakard et al., 2023). Risk assessments also suggest that future warming may make seaweed farming unviable in some current production regions, which means adaptation planning must account for the possibility that incremental adjustments will not always be enough (Kim et al., 2024).

7.2 Limitations regarding the adoption of adaptation technologies and investment costs

Although adaptation options such as selective breeding, diversification, improved nursery systems, and offshore expansion are widely discussed, their adoption is limited by technical complexity and cost. Reviews of climate-resilient aquaculture identify selective breeding, species diversification, and advanced systems as leading adaptation pathways, but more complex solutions generally require greater expertise and become less accessible as costs rise (Yadav et al., 2024). This constraint is especially relevant for kelp farming because resilience strategies often depend on research-intensive interventions such as breeding for tolerance, microbiome manipulation, or engineering systems suited to exposed environments (Veenhof et al., 2024).

Economic barriers also extend beyond farm hardware to the full production chain. Techno-economic modeling of kelp nurseries shows that reducing grow-out duration, increasing labor capacity, and de-risking energy-efficient systems are key priorities for lowering costs, while wider industry analyses point to operational optimization, weak supply chains, market uncertainty, and difficulty achieving economically viable scale as persistent obstacles (Coleman et al., 2022; Canvin et al., 2025). Even when seaweed farming is sometimes described as low-investment in principle, expansion into new regions or more climate-resilient production models often requires substantial infrastructure, financing, logistics, and external support that many small or early-stage producers do not have (Canvin et al., 2025).

7.3 Insufficiencies in policy support and management system development

Policy and management systems have generally not kept pace with the adaptation needs of aquaculture. National climate adaptation strategies often acknowledge climate risks broadly but seldom include aquaculture-specific measures, even though aquaculture needs to be integrated into national and regional adaptation plans to avoid being disadvantaged by policies designed for other sectors. For kelp farming, this gap is particularly important because farm siting, environmental monitoring, biosecurity, and licensing all require governance systems that can respond to changing climatic conditions rather than assuming static baselines.

Existing governance frameworks also tend to be fragmented, rigid, and overly reactive. Legal analysis of marine aquaculture adaptation in Chile found poor implementation of committed measures, lack of strategic vision, and planning and leasing systems too inflexible to support effective adaptation. Similar concerns appear in broader seaweed policy debates, where regulatory complexity, exclusion from carbon-accounting frameworks, and the need for standardized valuation and long-term conservation strategies continue to slow investment and coordinated management development (Chandrani et al., 2024; Canvin et al., 2025).

8 Conclusions and Future Outlook

Kelp aquaculture is likely to remain a strategically important component of climate-resilient marine food systems, but its future will depend on whether adaptation keeps pace with increasingly complex environmental change. Across the literature, the dominant message is that warming, altered seasonality, extreme events, and biological stressors are already reshaping cultivation risks, while the sector still retains strong potential to support food production, ecosystem services, and broader sustainability goals. Current evidence shows that climate change affects kelp aquaculture through multiple interacting pathways rather than through warming alone. A recent global meta-analysis found that ocean warming has strong negative effects on kelps across growth, reproduction, and survival, while acidification alone is generally weaker but can still impair reproduction; experimental work on bull kelp similarly shows that higher temperature reduces gametophyte survival and offspring production, even when lower pH has less negative effects on some early stages.

From an industry perspective, these physiological responses translate into operational risks such as lower biomass yield, altered biochemical composition, greater disease vulnerability, and damage from marine heatwaves, storms, and freshwater inputs. Reviews focused on North Atlantic seaweed aquaculture identify abiotic change, extreme events, and disease as major climate-related threats, while broader aquaculture syntheses show that harmful algal blooms, salinity change, and shifting ecological dynamics further complicate farm management and sustainability planning. The effects of climate change are also uneven across regions and species, which means exposure cannot be generalized from one farming area to another. Species farmed near their upper thermal limits are expected to be most vulnerable, whereas some colder regions may temporarily gain suitability as temperature or ice constraints relax; similarly, assessments of marine aquaculture potential project heterogeneous geographic gains and losses but an overall greater probability of declines under continued warming.

A comprehensive understanding therefore requires integrating farm biology with local oceanography, infrastructure limits, and socioeconomic context. Resilience studies in coastal farming communities show that climate impacts do not act on production alone but also on livelihoods, adaptive capacity, and equity, reinforcing the need to frame kelp aquaculture as a social-ecological system rather than only a biological crop system. The most consistently supported adaptation strategies are future-proof site selection, selective breeding or trait selection, ecosystem-based farm design, and stronger environmental monitoring. Reviews of North Atlantic seaweed aquaculture identify site selection, breeding and microbiome manipulation, and restorative aquaculture as the three main resilience pathways, while general climate-resilient aquaculture reviews similarly emphasize selective breeding, diversification, ecosystem-based management, and advanced systems as core adaptation tools.

These strategies appear effective when matched to the dominant local stressors, but evidence for each remains uneven. Site selection is strengthened by improved oceanographic and climate modelling, and biotechnology-oriented approaches such as tissue culture, selective breeding, and genetic engineering show promise for improving stress tolerance and yield; however, many of these interventions are still developing, and their commercial performance under open-water farming conditions is not yet fully resolved. Some adaptation benefits are already measurable at farm scale. Seaweed farms can buffer local acidification, with *Saccharina japonica* farms showing mean pH increases of about 0.10 and reduced pCO_2 relative to surrounding waters, which supports the view that farming can create localized refugia from acidification and deoxygenation.

Even so, adaptation effectiveness should not be judged only by whether kelp survives climate stress. Large-scale farming can introduce trade-offs such as habitat disruption, nutrient competition, or uncertain carbon benefits, so strategies are most credible when paired with habitat-friendly practices, IMTA, and rigorous monitoring and regulation rather than treated as universally beneficial solutions. Future development should prioritize breeding and seed systems, predictive farm planning, and cultivation technologies that are robust under a warmer and more variable ocean. The literature points to opportunities in omics-assisted breeding, targeted microbe treatments, and wider use of resilient species or strains, while also highlighting offshore farming and advanced monitoring as promising directions for sustaining production under climate stress. At the same time, the next phase of industry development will require stronger supporting systems beyond farm technology alone. Reviews from Norway and Tanzania both show that climate resilience depends on adapted regulatory frameworks, coordinated support, farmer training, and investment in improved varieties and knowledge transfer, especially where producers have limited capacity to absorb climate shocks on their own.

Another major priority is to build credible frameworks for environmental accounting and risk governance. Seaweed carbon accounting remains poorly developed, and robust monitoring, reporting, and verification systems are still needed to quantify sequestration pathways, evaluate trade-offs, and distinguish realistic climate services from claims that outpace the science. In the longer term, a climate-resilient seaweed industry will likely emerge from cross-sector integration rather than from farm expansion alone. Recent syntheses call for stronger global research collaboration, integration of new technologies, and development of robust value chains and circular bioeconomy pathways so that seaweed farming can support food security, low-carbon materials, and sustainable coastal livelihoods under climate change. Kelp farming under climate change is therefore best understood as a conditional opportunity: the sector shows real adaptive potential, but durable success depends on combining biological innovation, careful siting, ecological safeguards, and supportive institutions. Future progress will be strongest where resilience is pursued as a system-level strategy, not as a single technical fix.

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