

Feature Review

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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 CO₂, ocean warming, acidification, altered salinity regimes, and more frequent extreme events. Atmospheric CO₂ 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,