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