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.