

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).

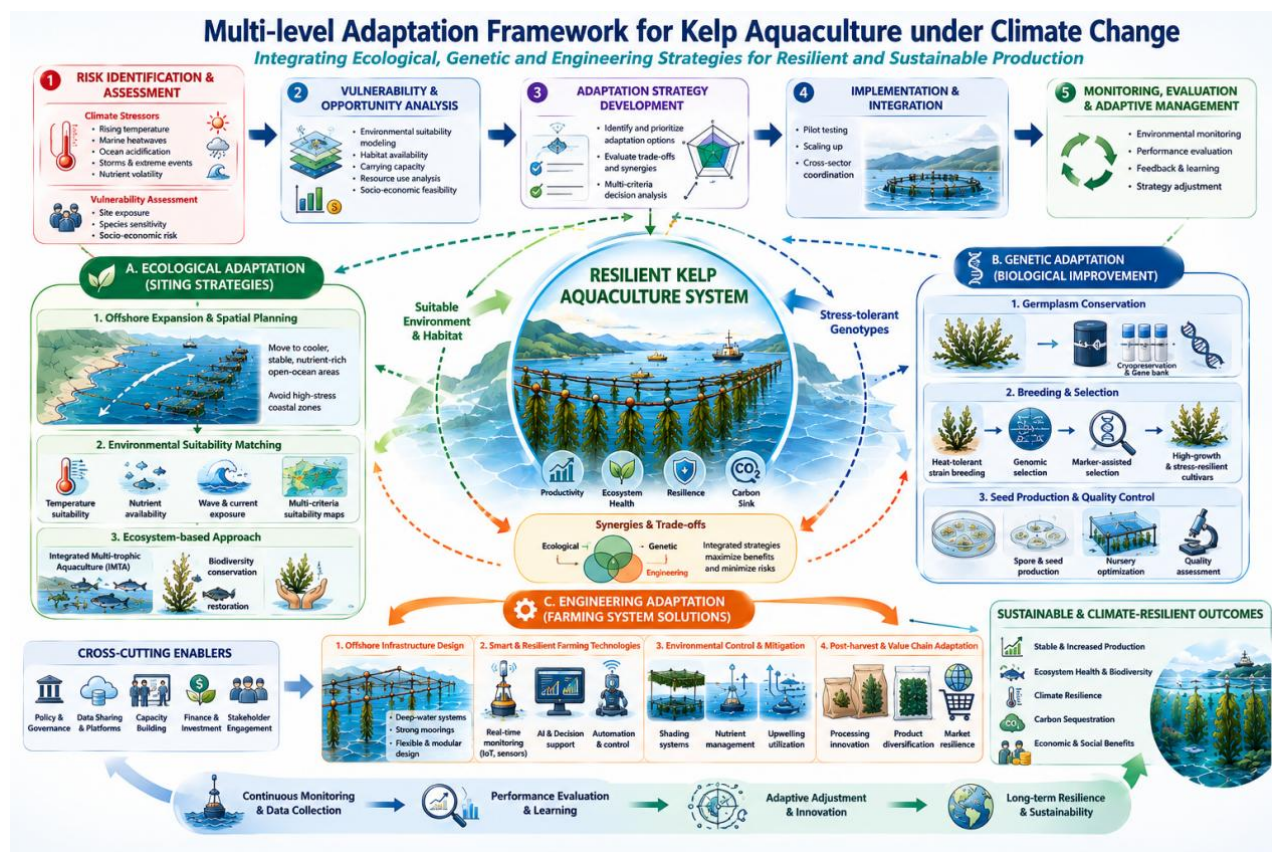


Figure 2 Multi-level adaptation framework for kelp aquaculture under climate change integrating ecological, genetic, and engineering-based strategies

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 CO₂, 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).