

## Climate-Resilient Aquaculture: Strategies for Sustainable Fish Production in a Changing Climate

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### Abstract

Climate change is placing aquaculture and culture-based fisheries under increasing stress, threatening global food security and the livelihoods of millions. Rising temperatures, unpredictable floods and droughts, ocean acidification, and shifts in salinity are disrupting fish growth, survival, and productivity. This article reviews the major environmental stressors affecting freshwater, brackish water, coastal, inland saline, cold-water, ornamental, and culture-based fisheries, and highlights climate-resilient adaptations now in practice. Approaches such as integrated multi-trophic aquaculture, recirculating aquaculture systems, selective breeding, species diversification, and habitat-based protection measures can help maintain production despite adverse conditions. The discussion highlights how innovative technologies, nature-based solutions, and enhanced management strategies can mitigate the impacts of climate change while supporting local economies. Building resilience in aquaculture is essential to ensuring a stable and sustainable fish supply for the future.

**Keywords:** Climate change, Aquaculture, Resilience, Fisheries adaptation, Environmental stressors

### Introduction

Aquaculture, the farming of fish, shellfish, and aquatic plants, is one of the fastest-growing food production sectors worldwide. It plays a vital role in ensuring food security, generating income, and supporting rural livelihoods. However, climate change poses serious challenges to aquaculture systems by altering water temperature, salinity,

rainfall patterns, and ocean chemistry. These changes lead to reduced productivity, higher disease outbreaks, and the loss of critical habitats.

In recent decades, extreme weather events such as floods, droughts, and cyclones have become more frequent, impacting both coastal and inland aquaculture. Developing countries, where large populations depend on aquaculture for affordable protein, are particularly vulnerable. To secure future fish production, it is essential to adopt climate-resilient strategies that minimize environmental risks while sustaining economic benefits. This article explores the key stress factors affecting aquaculture and highlights adaptation measures that can help the sector thrive in an era of climate uncertainty.

### Climate Resilience Strategies in Diverse Aquaculture Sectors

Freshwater aquaculture, comprising earthen ponds, tanks, raceways, and reservoir-based systems, is responsible for a substantial proportion of global aquaculture production. These systems are highly sensitive to hydrological regimes, making them particularly vulnerable to climate-induced changes in rainfall patterns, river discharge, and ambient temperatures. Elevated water temperatures accelerate metabolic rates in cultured finfish, increasing their oxygen and feed requirements while simultaneously decreasing dissolved oxygen solubility, thus predisposing the culture environment to hypoxic events. This oxygen deficit, combined with prolonged thermal stress, can lead to immunosuppression, heightened susceptibility to bacterial and parasitic pathogens, and enhanced proliferation of harmful algal blooms such as *Microcystis aeruginosa*. In regions like the Indian Sundarbans, climate-resilient adaptations include carp polyculture, integrated fish–rice systems, and the incorporation of salt-tolerant and air-breathing species such as *Oreochromis niloticus*, *Clarias batrachus*, and *Pangasius sutchi*. These measures, alongside structural interventions such as dyke reinforcement, predator-exclusion netting, and strategic planting of shade trees and emergent macrophytes, help buffer the impacts of salinity intrusion, flooding, and thermal extremes. Nutritional interventions, including the use of immunostimulants like fucoidan and propolis extracts, have shown efficacy in mitigating physiological stress under fluctuating temperatures.

Brackish water and coastal aquaculture, dominated by penaeid shrimp (*Penaeus vannamei*, *Penaeus monodon*) and bivalve mollusks (e.g., oysters, mussels, clams), is especially susceptible to the synergistic effects of sea-level rise, saline water intrusion, intensified storm surges, and ocean acidification. Acidified conditions, resulting from elevated CO<sub>2</sub> levels,

impair shell formation in calcifying organisms by reducing carbonate ion availability, leading to thinner shells and reduced market value. Selective breeding programs have demonstrated potential in enhancing calcite biomineralization and resistance to diseases such as white spot syndrome virus (WSSV) in shrimp. Integrated Multi-Trophic Aquaculture (IMTA) systems—co-culturing shrimp or finfish with filter-feeding bivalves and macroalgae such as *Gracilaria edulis* or *Kappaphycus alvarezii*—help assimilate excess nutrients, sequester carbon, and stabilize pH. Coastal bio-shielding through mangrove reforestation not only mitigates erosion and wave energy but also serves as a carbon sink and nursery habitat for wild aquatic species. In Vietnam and Bangladesh, shrimp–tilapia–seaweed polyculture has proven particularly effective in reducing feed costs and improving environmental conditions.

Inland saline aquaculture exploits groundwater and surface water bodies with salinity levels exceeding 10–15 ppt, often unsuitable for agriculture but viable for euryhaline finfish and crustaceans. Culture of *P. vannamei*, *Oreochromis mossambicus*, and select Indian major carps adapted to elevated ionic concentrations has expanded significantly in saline-prone states like Haryana and Rajasthan, India. Salinity-tolerant halophytes such as *Distichlis spicata* planted along pond peripheries act as biofilters for nutrient-rich effluents, reducing ammonia and nitrite levels, and simultaneously producing biomass for livestock feed. Controlled breeding of salinity-hardy broodstock has been prioritized to ensure seed availability and genetic resilience under fluctuating salinity regimes. In mixed agro-aquatic models, saline aquaculture is integrated with salt-tolerant crops, maximizing land use efficiency and economic returns.

Coldwater fisheries, largely focusing on salmonids including rainbow trout (*Oncorhynchus mykiss*) and Atlantic salmon (*Salmo salar*), are experiencing pronounced climate stress due to warming river and sea surface temperatures, shifts in precipitation patterns, and the emergence of novel pathogens like *Gyrodactylus salaris* and bacterial coldwater disease (*Flavobacterium psychrophilum*). Selective breeding programs are actively producing thermotolerant and pathogen-resistant strains. Hatchery-based acclimation protocols expose shellfish and finfish fry to gradual pH and temperature shifts to enhance resilience before transfer to grow-out facilities. Offshore polyculture installations combining finfish with bivalves and kelp act as environmental buffers, absorbing dissolved nutrients, sequestering CO<sub>2</sub>, and dampening temperature fluctuations within the culture zone.

Ornamental fisheries, which supply high-value species such as cardinal tetras (*Paracheirodon axelrodi*), green neon tetras (*P. simulans*), and clownfish (*Amphiprion ocellaris*), face unique

challenges due to narrow optimal thermal and water chemistry ranges. Controlled environment recirculating aquaculture systems (RAS) provide year-round stability but require advanced management skills and higher capital investment. Comparative studies on thermal tolerance indicate species-specific climate resilience, with *P. simulans* exhibiting higher survival under simulated warming scenarios compared to *P. axelrodi*, highlighting the importance of species selection for long-term viability. Ornamental aquaponics, integrating ornamental fish culture with hydroponic production of herbs and leafy vegetables, offers both environmental control and revenue diversification, though system failures can cause total crop and stock losses.

Culture-based fisheries, which rely on stocking hatchery-reared seed into natural or artificial water bodies for grow-out on natural food resources, are sensitive to climatic variability in hydrology. In Assam's floodplain wetlands (beels), pen culture of climate-resilient indigenous species like *Amblypharyngodon mola*, *Gudusia chapra*, and *Puntius sophore* alongside major carps has proven sustainable when stocking densities are maintained to prevent water quality deterioration. Protective netting prevents escapement during high-flow events. Open-water IMTA systems in lakes and reservoirs combine finfish with bivalves and macroalgae to regulate nutrient levels, stabilize thermal profiles, and enhance ecosystem services. Incorporating predictive hydrological models, such as the HEC-HMS and climate variability models like HadCM3, into management plans allows for more accurate stocking and harvest schedules, reducing climate-related losses.

## Conclusion

Climate change is no longer a distant threat for aquaculture; it is a present-day challenge influencing every stage of production, from seed rearing to harvest. Rising temperatures, shifting salinity, and extreme weather events have already disrupted fish growth, survival, and yields in many parts of the world. The examples from freshwater, brackish water, coastal, inland saline, cold-water, ornamental, and culture-based fisheries show that adaptation is possible when farmers and researchers work together. Climate-resilient strategies such as integrated multi-trophic aquaculture, recirculating aquaculture systems, selective breeding, and species diversification are proving effective in maintaining production under variable conditions. Nature-based solutions like mangrove restoration and agro-aquatic integration offer both environmental protection and economic benefits. However, broader adoption will require supportive policies, targeted funding, and training to help farmers transition to these methods.

By investing in resilient systems now, the aquaculture sector can safeguard livelihoods, protect ecosystems, and ensure a stable fish supply for future generations, even in the face of a rapidly changing climate.

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