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Climate-Smart Aquaculture: Building Resilient Food Systems in a Changing Climate

*Dona Merli A R and Agnes Daney Angela S
Dr. M.G.R. Fisheries College and Research Institute, Ponneri, Thiruvallur, Tamil Nadu
*Corresponding Author's email: donamerli2004@gmail.com

Aquaculture is the world's fastest-growing food production sector, surpassing capture fisheries for the first time in 2022 with a global output of 130.9 million tonnes and per capita supply of 20.7 kg. Yet this cornerstone of global food security faces escalating threats from climate change, rising water temperatures, ocean acidification, extreme weather events, sea-level rise, and harmful algal blooms that could reduce yields by up to 30% in vulnerable regions by 2030, costing the sector an estimated USD 10 billion annually. Climate-Smart Aquaculture (CSAq) has emerged as an evidence-based framework built on three interdependent pillars: adaptation to climate variability, mitigation of greenhouse gas (GHG) emissions, and sustainable intensification of production. This article synthesizes current scientific knowledge on CSAq, drawing on peer-reviewed literature across marine biology, environmental science, and food systems policy. It reviews principal climate threats and critically evaluates the most promising response strategies: Integrated Multi-Trophic Aquaculture (IMTA), Recirculating Aquaculture Systems (RAS), biofloc technology, selective breeding, precision digital technologies, and blue carbon sequestration alongside the socio-economic and policy dimensions essential for a climate-smart transition. The article concludes that accelerating CSAq adoption demands coordinated investment in technology, inclusive governance, and climate finance, with particular urgency for vulnerable coastal communities in the Global South.

Keywords: Climate-Smart Aquaculture; ocean acidification; integrated multi-trophic aquaculture; recirculating aquaculture systems; greenhouse gas mitigation; blue carbon; food security; climate adaptation; selective breeding; precision aquaculture

Introduction

Global aquaculture reached 130.9 million tonnes in 2022, surpassing wild capture fisheries and providing livelihoods to hundreds of millions worldwide (FAO, 2024). The sector is central to SDG 2 (Zero Hunger), yet its growth trajectory is increasingly imperilled by climate change a challenge that conventional reactive management cannot adequately address (Maulu et al., 2021). Climate-Smart Aquaculture (CSAq) was conceptualized within FAO's Climate-Smart Agriculture framework (2010) and targets aquaculture's unique vulnerabilities by promoting resilience, productivity, and a reduced environmental footprint (FAO, 2023). CSAq scholarship has grown substantially, peaking at 64 publications annually in 2023, led by the United States, India, China, and the United Kingdom (Kolawole et al., 2024). Its three pillars are: adaptation (resilience to climate variability); mitigation (reducing GHG emissions); and sustainable intensification (enhanced productivity with minimal environmental degradation).

Climate Change Impacts on Aquaculture

Temperature and Dissolved Oxygen. Temperature governs physiology, immunity, growth, and reproduction across all farmed aquatic species (Hossain et al., 2025). Rising sea surface temperatures reduce dissolved oxygen, disrupt feeding, and accelerate pathogen transmission. Without adaptive management, climate variability could cut yields by up to 30% in vulnerable regions by 2030, with current annual sector losses already estimated at USD 10 billion (MACIS, 2024; FAO, 2023). Crustaceans shrimp, prawns, crabs are especially sensitive to thermal stress affecting moulting and immunity.

Ocean Acidification. CO_2 absorption reduces seawater pH, impairing calcification in oysters, abalone, and sea urchins and lowering their survival and market value (Fitzer et al., 2018; Islam et al., 2022). Acidification also elevates bioaccumulation of chemical contaminants in bivalves, raising food safety concerns (Maulvault et al., 2018).

Extreme Events, Sea-Level Rise, and Salinity Intrusion. Intensifying cyclones, floods, and droughts destroy aquaculture infrastructure and disrupt supply chains. Sea-level rise drives salinity intrusion into coastal ponds and inland water bodies, altering species suitability and reducing productivity. Bangladesh's coastal sector exemplifies the compounding damage of cyclone flooding and salinity shifts (Amjath-Babu et al., 2025).

Harmful Algal Blooms and Disease. Warmer, nutrient-enriched waters intensify harmful algal blooms (HABs), producing toxins lethal to farmed species, while elevated temperatures accelerate pathogen spread and disease burden across production systems (Basti et al., 2019).

Key Strategies in Climate-Smart Aquaculture

Integrated Multi-Trophic Aquaculture (IMTA). IMTA co-cultivates species from different trophic levels: finfish (fed), seaweeds (inorganic extractive), and bivalves (organic extractive) so that the metabolic waste of one species becomes a resource for another (Chopin, 2024). Climate-smart benefits are fourfold: (i) *carbon sequestration* one tonne of dry seaweed absorbs approximately 960 kg CO_2, and global seaweed farming could sequester an additional 0.3 $GtCO_2e$/year by 2050 (Farghali et al., 2023; OCTO, 2024); (ii) *nutrient bioremediation* bivalves and macroalgae remove excess nitrogen and phosphorus, preventing coastal eutrophication; (iii) *acidification mitigation* seaweeds reduce local seawater pCO_2 and oyster shells act as carbonate sinks (PHAROS Project, 2024); and (iv) *economic resilience*. IMTA is demonstrably more profitable than monoculture salmon under most tested scenarios (Chopin, 2024). Coupling IMTA with selective breeding for trans-generational acclimatization offers a dual-track strategy for bivalve farms in acidification-prone zones (Tan & Zheng, 2020).

Recirculating Aquaculture Systems (RAS) and Aquaponics. RAS are land-based, closed-loop facilities that filter and recycle water continuously, achieving high production densities while minimising water use, disease incidence, and environmental discharge (Ahmed & Turchini, 2021). Their insulation from external climate variability floods, droughts, salinity fluctuations, ocean acidification and capacity for year-round production make them a cornerstone climate adaptation tool. Powering RAS with renewable energy substantially reduces their carbon footprint; one US study showed switching to renewables cut RAS salmon emissions from 7.01 to 3.39 kg CO_2eq/kg live weight (Gupta et al., 2024). Integration with aquaponics further closes nutrient cycles and reduces the combined carbon footprint of fish and vegetable production (Jal et al., 2024).

Biofloc Technology (BFT). BFT promotes microbial floc growth in culture water, converting nitrogenous waste into supplementary protein while minimising water exchange and pathogen introduction. It reduces dependence on costly external feeds and is particularly suited to shrimp and tilapia farming in water-scarce regions increasingly stressed by climate change (Islam et al., 2022; Bhattacharyya et al., 2020).

Selective Breeding and Genomic Improvement. Genetic programs selecting for heat tolerance, disease resistance, and feed conversion efficiency are a proactive long-term strategy for climate resilience (Devi et al., 2025; Du et al., 2021). Genomic selection and marker-assisted breeding are accelerating improvements for traits previously inaccessible to conventional programs, including improved rohu (*Labeo rohita*) strains in India and thermally tolerant tilapia for tropical systems. Combining genomic programs with IMTA management provides a complementary acclimatization pathway for acidification-sensitive bivalves (Tan & Zheng, 2020).

Precision Aquaculture and Digital Technologies. IoT sensors, AI, and satellite monitoring enable dynamic, data-driven responses to climate stressors. Real-time tracking of dissolved oxygen, temperature, pH, and salinity paired with predictive analytics has reduced farm mortality by up to 40% in trials (MDPI, 2025). Digital twins allow producers to simulate system responses to temperature anomalies before real-world intervention (Aquaculture Magazine, 2025). Satellite sea surface temperature data supports early warnings of marine heatwaves, guiding timely harvest and stocking decisions (Zhang et al., 2024). Blockchain further supports supply chain traceability and sustainability certification (Springer Nature / Aquaculture International, 2025).

GHG Emissions, Blue Carbon, and Policy

Emissions and Mitigation. Aquaculture contributes approximately 0.45% of global anthropogenic GHG emissions, yet the footprint of fed finfish averages around 3,271 kg CO_2e per tonne wet weight, with feed production as the largest single source (MacLeod et al., 2020; Froehlich et al., 2022). Key mitigation pathways include alternative feeds (insect protein, algae, plant-based ingredients), renewable energy for RAS, expansion of low-emission seaweed and shellfish culture, and Life Cycle Assessment (LCA) to pinpoint hotspots across production systems (AQUADAPT, 2024; Li et al., 2025).

Blue Carbon. Aquatic ecosystems store an estimated 93% of global biospheric carbon, with approximately 30% of annual CO_2 emissions sequestered in mangroves, seagrasses, and coastal sediments (Nellemann et al., 2009). Global mollusk production alone may sequester 0.97–1.93 million MT of blue carbon annually (Ahmed et al., 2019). Integrating mangrove restoration around pond farms and embedding blue carbon conservation into aquaculture siting and management decisions represents a high-value ecosystem-based component of CSAq (NPJ Ocean Sustainability, 2024).

Policy and Socio-Economic Dimensions. Enabling policy environments are indispensable for CSAq adoption at scale. FAO's Climate-Smart Agriculture Sourcebook (2024) identifies three strategic objectives: environmental, social, and economic sustainability; reducing vulnerability and building resilience; and enabling GHG mitigation across value chains. National Adaptation Plans and NDCs must explicitly incorporate aquaculture to unlock climate finance. The Green Climate Fund and blended finance mechanisms are primary funding pathways, supporting both "hard" investments (RAS, IMTA installations, flood barriers) and "soft" investments (early warning systems, training, institutional capacity) (Amjath-Babu et al., 2025). Gender-inclusive extension services are equally essential, as women constitute a significant share of the small-scale aquaculture workforce (Islam, 2025). Critically, most CSAq research originates in developed countries, while developing nations which bear the greatest climate vulnerability remain underrepresented; this geographic imbalance in knowledge production must be urgently addressed (Kolawole et al., 2024).

Conclusion

Climate-Smart Aquaculture provides a scientifically grounded, multidimensional pathway to sustaining aquatic food production in a warming world. By integrating IMTA, RAS, biofloc technology, genomic improvement, precision digital tools, and blue carbon strategies underpinned by inclusive governance and dedicated climate finance CSAq can simultaneously deliver food security, GHG mitigation, and ecosystem resilience. Accelerating this transition is most urgent for the vulnerable coastal communities of the Global South, where both the risk and the transformative potential of CSAq are greatest.

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