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Adapting Aquaculture to Climate Change: Challenges and Sustainable Solution

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Aquaculture, the fastest-growing food production sector globally, faces mounting threats from climate change, including rising water temperatures, ocean acidification, altered precipitation patterns, and increased frequency of extreme weather events. These environmental shifts disrupt fish physiology, aquatic ecosystem dynamics, pathogen proliferation, and feed resource availability, collectively undermining the productivity and sustainability of both marine and freshwater aquaculture operations. This article reviews the major climate-related challenges confronting the aquaculture sector and synthesizes current and emerging adaptive strategies spanning site selection, species diversification, selective breeding, integrated multi-trophic aquaculture (IMTA), advanced water quality management, and policy-level governance frameworks. Achieving climate-adaptive aquaculture demands coordinated action among farmers, researchers, governments, and international bodies to safeguard aquatic food security for future generations.

Keywords: aquaculture, climate change, ocean acidification, thermal stress, integrated multi-trophic aquaculture, climate adaptation, food security, sustainable fisheries

Introduction

Aquaculture has emerged as one of the most critical pillars of global food security, currently supplying over half of all fish consumed by humans worldwide (FAO, 2022). Its rapid expansion averaging nearly 7% annual growth over the past three decades positions aquaculture as an indispensable component of the global protein supply chain, particularly as wild capture fisheries approach or exceed maximum sustainable yields (Naylor et al., 2021). However, this trajectory of growth is now imperilled by the accelerating pace of climate change. The global mean surface temperature has already risen approximately 1.1°C above pre-industrial levels, and projections under moderate and high emission scenarios forecast further increases of 2–4°C by 2100 (IPCC, 2021). Aquaculture operations which depend on stable water quality, predictable seasonal conditions, and healthy aquatic ecosystems are particularly vulnerable.

Impacts of Rising Water Temperature on Farmed Species

Temperature is arguably the single most influential abiotic variable governing the physiology, behaviour, reproduction, and immunity of aquatic organisms. Most farmed species are ectothermic meaning their metabolic rate is directly tied to ambient water temperature and therefore highly sensitive to even modest thermal fluctuations. For salmonids such as Atlantic salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*), which are among the most economically significant farmed species in temperate regions, optimal growth occurs within a narrow temperature range of 12–16°C. Sustained exposure to temperatures exceeding 20°C induces heat stress responses, suppresses immune function, reduces feed conversion efficiency (Oldham et al., 2016). Conversely, tropical and subtropical aquaculture species such as tilapia (*Oreochromis niloticus*), shrimp (*Litopenaeus vannamei*), and pangasius catfish (*Pangasianodon hypophthalmus*) exhibit broader thermal tolerances but are nonetheless affected by extreme temperature events and seasonal variability. Rising temperatures can accelerate metabolic rates and compress growth cycles in the short term; however, chronic thermal stress reduces reproductive output, increases aggression, and causes progressive organ dysfunction (Hossain et al., 2020). Furthermore, warmer water holds less dissolved oxygen, creating hypoxic conditions that pose acute risks in densely stocked pond and cage culture systems.

Ocean Acidification and Its Consequences for Marine Aquaculture

Alongside warming, the ocean absorbs approximately 25–30% of anthropogenic CO2 emissions annually, triggering a process known as ocean acidification (OA). Since the Industrial Revolution, ocean surface pH has declined from approximately 8.2 to 8.1 a shift representing a roughly 26% increase in hydrogen ion concentration (Doney et al., 2009). While this change may appear modest in absolute terms, it has profound biological implications, particularly for organisms that construct calcium carbonate (CaCO3) shells or skeletons. Bivalve molluscs including oysters (*Crassostrea gigas*, *Ostrea edulis*), mussels (*Mytilus edulis*), clams (*Mercenaria mercenaria*), and scallops (*Argopecten irradians*) are among the most economically valuable and ecologically sensitive casualties of OA. Reduced carbonate ion concentrations in seawater impair calcification rates, increase shell dissolution, and weaken structural integrity. Beyond calcification, OA affects sensory systems, reproductive behaviour, and predator avoidance in a range of marine species. Marine finfish such as sea bream (*Sparus aurata*) and sea bass (*Dicentrarchus labrax*) exhibit altered olfactory function and otolith (hearing organ) development under elevated pCO2, with potential consequences for hatchery-reared stock performance and wild-stock recruitment.

Disease Outbreaks and Emerging Pathogen Dynamics

Climate change functions as a 'threat multiplier' for aquatic disease dynamics, amplifying existing vulnerabilities and creating conditions favourable to novel pathogen emergence and spread. The intersection of thermal stress, compromised host immunity, and pathogen ecology represents one of the most operationally disruptive climate-related challenges facing aquaculture practitioners globally (Shinn et al., 2015). Elevated water temperatures accelerate the replication rates of many bacterial, viral, and parasitic pathogens. *Aeromonas hydrophila*, a ubiquitous freshwater bacterium, undergoes dramatically enhanced virulence above 25°C and has been implicated in mass mortality events in tilapia, catfish, and carp culture across South and Southeast Asia during anomalously warm seasons (Rana et al., 2022). Similarly, *Vibrio spp.* — marine and estuarine bacteria responsible for vibriosis in shellfish and finfish — thrive at warmer temperatures and have expanded their geographic distribution poleward in tandem with rising sea surface temperatures. Altered precipitation and runoff patterns associated with climate change introduce additional epidemiological complexity. Heavy rainfall events can rapidly dilute salinity in coastal farms, stress euryhaline species, carry elevated loads of agricultural contaminants and terrestrial pathogens into farm environments, and trigger harmful algal blooms (HABs) that produce biotoxins lethal to both farmed and wild aquatic species.

Adaptive Strategies: Technology, Management, and Ecological Innovation

Despite the severity of climate-related threats, the aquaculture sector possesses a diverse and expanding toolkit of adaptive strategies.

Selective Breeding and Genetic Adaptation

Selective breeding programmes targeting thermal tolerance, disease resistance, and reproductive robustness represent a long-term cornerstone of climate adaptation in aquaculture genetics. Atlantic salmon strains with improved tolerance to elevated temperatures have been developed through quantitative trait locus (QTL) mapping and marker-assisted selection (MAS), accelerating the rate of adaptive genetic change beyond what natural selection alone could achieve across human-relevant timeframes (Yáñez et al., 2020).

Integrated Multi-Trophic Aquaculture (IMTA)

IMTA systems co-cultivate species from different trophic levels typically combining fed species (e.g., salmon or sea bream) with extractive inorganic species (e.g., shellfish) and organic extractive species (e.g., seaweeds or deposit-feeding invertebrates) so that the nutrient and organic waste outputs of one species become productive inputs for another. This ecological engineering approach reduces waste accumulation, improves water quality, enhances system nutrient cycling efficiency (Chopin et al., 2012).

Advanced Water Quality Monitoring and Recirculating Aquaculture Systems

Recirculating Aquaculture Systems (RAS) — which maintain fish in high-density indoor tanks with continuous water treatment, oxygenation, and biofiltration — offer the most complete decoupling of aquaculture production from ambient environmental conditions. RAS technology enables precise control of temperature, salinity, pH, dissolved oxygen, and photoperiod, effectively insulating production against external climate variability.

Species and Site Diversification

Strategic diversification — both of cultured species and farming site selection — provides a practical hedge against climate-induced production variability. Investment in the commercial development of climate-hardy, thermally flexible species such as barramundi (*Lates calcarifer*), milkfish (*Chanos chanos*), and various microalgae offers alternatives where traditional species are becoming climatically marginal.

Conclusion

Climate change poses existential challenges to the future of aquaculture as we know it yet it also catalyses a necessary and long-overdue transformation of the sector toward greater ecological sophistication, technological innovation, and governance maturity. The evidence reviewed in this article demonstrates that while the threats rising temperatures, ocean acidification, intensified disease dynamics, and destabilised feed systems are real and already manifesting in measurable production impacts, an array of credible and increasingly field-validated adaptive strategies is available to farmers, policymakers, and researchers willing to invest in sector-wide resilience. The central message is one of urgency tempered by possibility: climate-adaptive aquaculture is achievable, but it demands integrated action across the genetic, technological, ecological, economic, and political dimensions of the sector.

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