Climate-induced stress and disease dynamics in aquaculture species

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Abstract

Climate change is increasing stress on aquaculture systems, significantly influencing farmed aquatic species' health and disease dynamics. Rising temperatures, altered salinity, and ocean acidification compromise immune function and physiological resilience in fish and shellfish, making them more susceptible to pathogens and parasites. Additionally, environmental fluctuations can facilitate the emergence, virulence, and transmission of infectious diseases, disrupting aquaculture productivity and sustainability. This review explores the complex interactions between climate-induced stressors and disease outbreaks in aquaculture, highlighting key mechanisms by which environmental stress affects host-pathogen dynamics. It also addresses the vulnerability of specific aquaculture species and production systems, drawing attention to critical regions at risk. Mitigation strategies, including adaptive management practices, improved disease surveillance, and selective breeding for resilience, are discussed as pathways to reduce the impact of climate change on aquaculture health. Understanding the multifactorial relationship between climate variables and disease ecology is essential for developing effective interventions and ensuring the long-term viability of aquaculture industries under changing climatic conditions.

Keywords: Climate-induced stress, Aquaculture species, Aquaculture industries

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Introduction

The food security of a population can be impacted by the economy or global supply chains due to aquaculture being the fastest-growing source of food (Islam, Kunzmann and Slater, 2022). However, the industry's capacity to manage many forms of climate change is progressively under greater strain (Saidova *et al.*, 2024). Changes such as increasing the severity of weather, sea temps, and precipitation alter the ecosystem (Shahjahan *et al.*, 2022). The ecosystem undergoing breakdown also leads to physiological stress in species known to be eliminated, reducing immunity while raising susceptibility to diseases (Milev *et al.*, 2024) (Sindhu, 2023). Climate fundamentals increase the control of emerging and spreading infectious agents, increasing the likelihood of outbreaks (Ytteborg *et al.*, 2023; Assegid & Ketema, 2023). The intricate stress on the environment becomes woven together between sustaining stresses interweaving with disease flow that becomes unique for different species and ecosystem elements (Bansal & Naidu, 2024). A host of new aquaculture regions integrate with existing ones, and remote studies emerge, exacerbating the issues of ethnos brought about by climate change (Vega-Heredia, Giffard-Mena and Reverter, 2024; Yadav *et al.*, 2024). Employed specialists and other academics focusing on emerging frameworks always look towards identifying active factors that assist these grand issues (Moretti and Tanaka, 2025). Directing research provides supporting resources that address resolving the balance between climate and disease and aiding the creation of new emerging opportunities (Maulu *et al.*, 2021; Iyengar and Bhattacharya, 2024). Understanding how aspects of climate change significantly assist in the eruption of new diseases aids in formulating biosecurity strategies appropriate for increasing temperatures for sustainable aquaculture systems (Nidhi *et al.*, 2024).

Climate change-related stressors affecting hosts' immune mechanisms and pathogens' efficacies include ocean temperature, acidity, salinity, and warmth (Bhanumathi and Sasirekhamani, 2024). The paper deconstructs the multifaceted mechanisms responsible for disease outbreaks in aquaculture systems. This paper offers important details on the aquaculture species and production methods most susceptible to diseases connected to climate change. Understanding the weaknesses of various areas and species helps us allocate resources and properly control hazards (Sharipov *et al.*, 2024; Chengula *et al.*, 2024). The present article suggests reasonable mitigating techniques to guarantee aquaculture's durability and well-being in changing conditions (Malhotra, 2025). These approaches comprise selective breeding for climate resilience, better disease surveillance, and adaptive management. The strategies are grounded in a synthesis of industrial practices and current research. Climate change greatly threatens aquaculture since it affects aquatic habitats and influences fish physiology, health, and output. The reviewed papers highlight the requirement of adaptive management and climate-resilient strategies to maintain aquaculture systems running in the face of rising temperatures, changing salinities, hypoxia, and new illnesses (Nagarajan and Jensen, 2010).

Climate Change Effects on Aquaculture Health and Immunity

The article at hand investigates how aquaculture is affected by climate change. Variations in temperature, pH, and low dissolved oxygen levels impair hosts' immune systems and increase their infection vulnerability (Muhala *et al.*, 2021). Focusing on the interaction of environmental stress, host vulnerability, and pathogen virulence helps one to highlight both the local and global consequences on fish health and production (Mitra *et al.*, 2023).

Climates-Resilient Strategies for Sustainable Aquaculture

The present project examines sustainable systems, including aquaponics, adaption strategies, species variety and selective breeding, and aquaculture's sensitivity to climate change (Kapoor and Iyer, 2024). Given rising temperatures, ocean acidity, and other environmental changes, it emphasizes the need of climate-resilient methods for the long-term survival of fish feed production systems (Agarwal *et al.*, 2024).

Physiological Stress in Aquatic Life from Climate Variability

This article investigates the physiological impacts of rising salinity and temperature on aquatic life. It looks at how rising greenhouse gas accumulation and upwelling resulting from climate change endanger fish life by producing hot and hypoxic conditions (Siddique *et al.*, 2022). Exothermic aquatic life is highly sensitive to climate change, so this article emphasizes the need to intervene immediately (Eckhart *et al.,* 2019).

Environmental Stressors and their Impact on Aquatic Species Physiology

In addition to this the environmental pressures most affecting aquatic life are reef acidification, hypoxia, changing salinity, and rising temperatures. These changes could make fish and shellfish more vulnerable to disease because of changed osmoregulation, slowed metabolic rates, and decreased immune reactions.

The Mercury over thermal tolerance can cause stress-induced behavioral and physiological changes, including reduced feeding, decreased growth, and increased mortality, as shown in Figure 1. Acidified waters can hinder mollusks' shell development and compromise fish's sensory ability. These pressures in aquaculture environments upset physiological homeostasis, which lowers resilience, reproduction, and disease susceptibility.

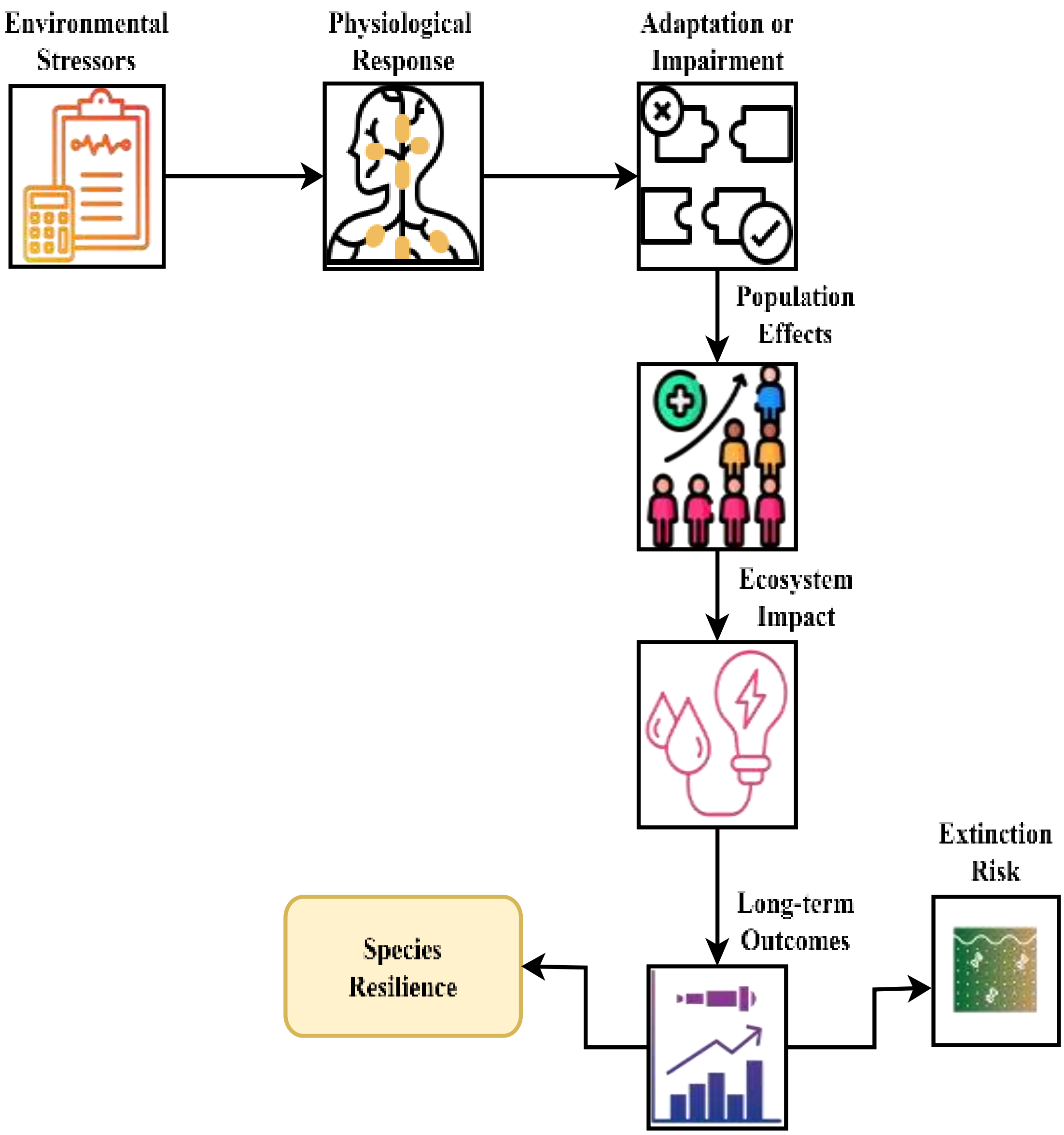

Figure 1: Environmental stressors and their impact representation.

Shifting Disease Patterns and Host-Pathogen Interactions

The warming planet is altering disease patterns in aquaculture systems and the dynamics of host-pathogen interactions. Variations in water temperature and other environmental pressures may impair the resistance to infection of aquatic life, hence increasing their susceptibility to illnesses.

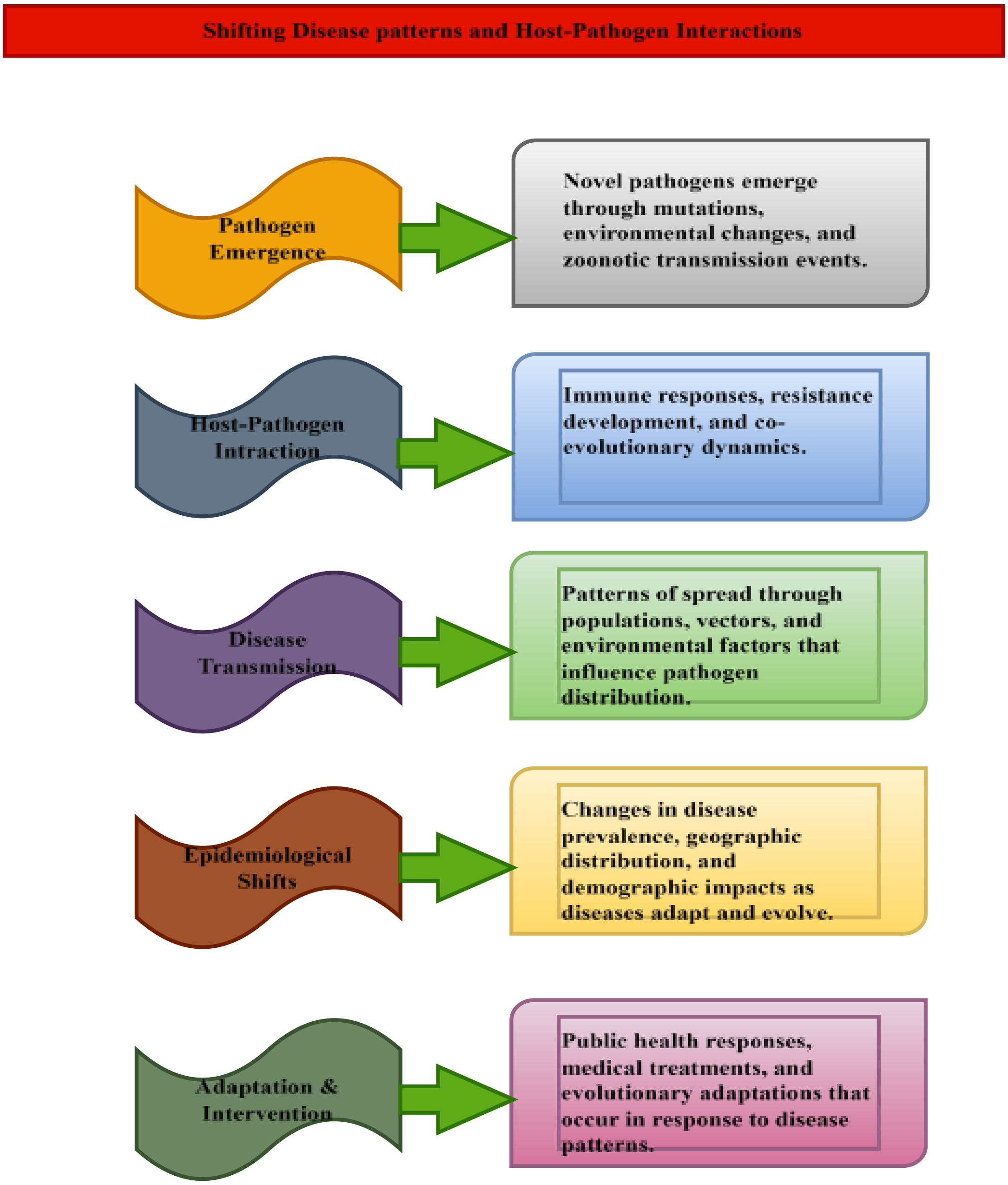

Figure 2: Overview of shifting disease patterns.

By raising the virulence of pathogens, heat waves can make diseases more contagious; salt and pH level changes can influence how well germs survive and spread Figure 2. Another probable result of these developments is the arrival of new diseases in regions once free of them. This puts aquaculture species' production and well-being at risk since the higher possibility of disease outbreaks in these systems compromises them.

Adaptive Strategies for Resilient Aquaculture Systems

The aquaculture industry needs adaptive strategies that boost resilience to lessen the consequences of climate change. These techniques include disease-resistant species breeding, recirculating aquaculture systems (RAS) to enhance water quality control, and diversifying species to distribute risk. Integrating multi-trophic aquaculture (IMTA) and other ecosystem-based approaches can enhance system stability through higher biodiversity and nutrient recycling. Using real-time monitoring systems for water quality and disease outbreaks also helps early identification and intervention. Two climate-resilient strategies that help sustain output while reducing environmental stress on aquatic species are changing stocking density and improving feeding strategies.

Comparative Susceptibility of Aquaculture Species to Climate-Induced Stressors

Separate aquaculture species' physiological characteristics and environmental tolerances help to explain their relative sensitivity to pressures driven by the climate. Although they may have trouble adjusting to changes in salinity, fish more suited to cooler waters, such as salmon and trout, are more at a disadvantage regarding temperature and hypoxia than fish more tolerant of higher temperatures.

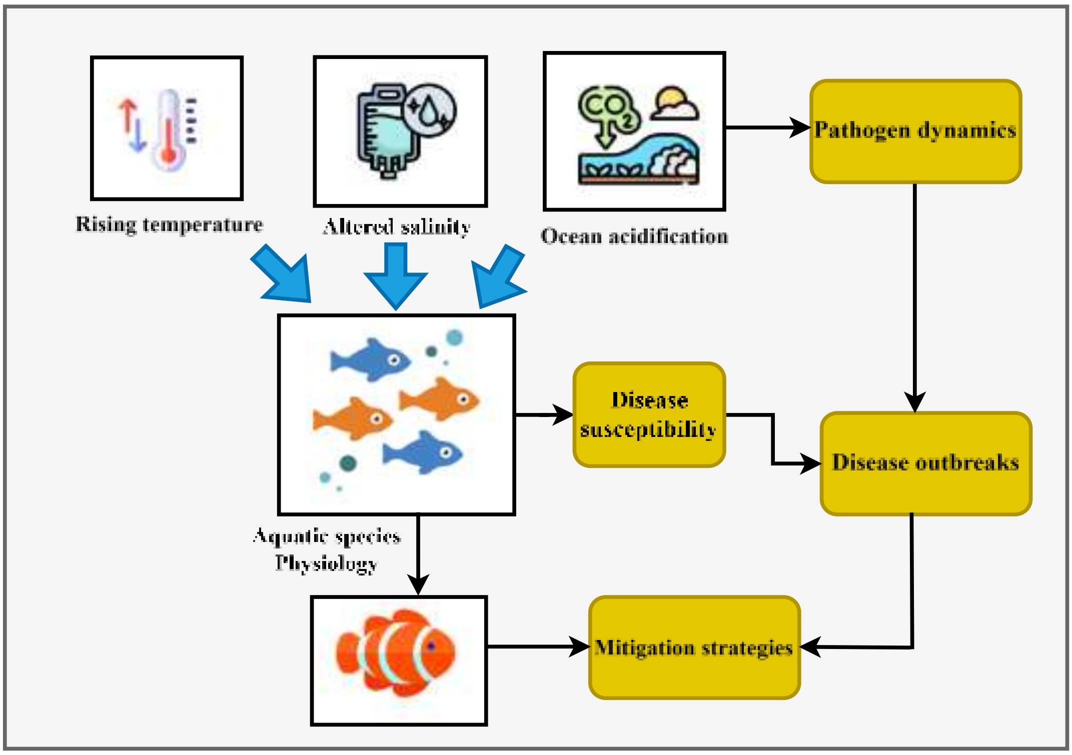

Figure 3: Susceptibility of aquaculture species.

Oysters and other shellfish are susceptible to the impacts of ocean acidification on their shell-forming capacity, as shown in Figure 3. We must grasp these species-specific vulnerabilities to create targeted management plans and ensure aquaculture enterprises can survive shifting climatic conditions.

Disease Outbreak Patterns Across Varied Climatic Conditions

Disease breakout patterns in aquaculture are thus likewise impacted by climate change since temperature, salinity, and oxygen levels all depend on it. Regarding the proliferation of infectious diseases, extreme heat can accelerate person-to-person transfer, speed their development, and trigger epidemics in previously undetected locations. Floods and storms will likely destroy aquaculture systems, creating nurseries for disease-carrying organisms. Further, altering water quality due to acidification or lack of oxygen causes additional stress for life in water. This may compromise their immune systems, thus elevating their susceptibility to diseases. Adaptive management planning measures are required to minimize the detrimental impacts of shifting trends in these diseased outbreaks.

Effectiveness of Mitigation Strategies in Different Aquaculture Settings

The extent to which these strategies work depends on that region's climate and ecosystem, as well as the scale of operations. In aquaculture, alleviation strategies may not elicit the desired impact due to variations in environment and species. In recirculating aquaculture systems, modern water treatment and management methods can reduce stressors such as water quality and high temperature, thus keeping the welfare of the fish healthy. Alterations to stocking levels, integrated multi-trophic aquaculture, and species diversification in coastal and open-water aquaculture systems may carve new pathways to combating climate stressors. Resistance to diseases through selective breeding coupled with real-time monitoring of the environment will further fortify resilience. Accompanied by stressors brought on by climate change, adaptive measures are hoped to be effective. Integrated review of disease dynamics, climate-induced stressors, and mitigation strategies in aquaculture systems shown in Table 1.

Table 1: Integrated review of disease dynamics, climate-induced stressors, and mitigation strategies in aquaculture systems.

Climate Stressor	Physiological Impact on Species	Disease Dynamics	Vulnerable Species/Systems	Geographic Regions at Risk	Mechanisms of Action	Mitigation Strategies
Rising Temperatures	- Impaired immune response- Increased metabolic stress	- Enhanced virulence- Faster pathogen replication- Outbreak frequency	Salmon, Tilapia, Shrimp	Tropics, Polar fringes	Alters host-pathogen balance weakens thermal tolerance	Selective breeding for heat resistance Early warning systems
Altered Salinity	- Osmotic stress- Reduced growth rate	- Opportunistic infections rise- Stress-induced immunosuppression	Shellfish (e.g., oysters, mussels), Brackish-water species	Coastal estuaries, Delta regions	Disrupts osmoregulation; weakens mucosal barriers	Salinity-adaptive aquaculture speciesWater quality management
Ocean Acidification	- Decreased shell formation- Acidosis in tissues	- Increased vulnerability to bacteria and parasites	Mollusks, Crustaceans	Coral reef zones, Acidifying coasts	CO_2 uptake reduces carbonate ions, damaging shells and immune resilience	Buffering Techniques in waterCO_2 emission reduction strategies

Low Dissolved Oxygen (DO)	- Hypoxia-induced organ dysfunction	- Favors anaerobic pathogens- Increases mortality during outbreaks	Warm-water fish, Bottom dwellers	Over-fertilized coastal regions	Warmer water holds less O_2, stressing respiration	Aeration systemsIntegrated aquaculture practices
Sudden Weather Extremes	- Thermal shock- Physical injury	- Disease outbreaks due to stress spikes and migration of pathogens	Freshwater pond systems, Floating cages	Monsoon-affected regions, Island nations	Causes rapid physiological shifts and shock responses	Infrastructure strengthening Disaster-resilient planning
pH Changes	- Altered enzyme activity- Reduced digestive efficiency	- Alters pathogen-host interactions	Sensitive fry/larvae, Breeding centers	Acid rain-prone regions, Urban aquaculture zones	pH fluctuations impair physiological processes	pH buffering systems real-time monitoring systems
Cumulative Stress Interactions	- Multi-system breakdown - Chronic immune suppression	- Frequent, multi-pathogen outbreaks	All intensive systems	Global (site-specific risks vary)	Synergistic stress amplifies pathogen colonization and reduces resistance	Ecosystem-based aquaculture management Resilience-focused R&D

Conclusion and Prospects

By exerting stresses that weaken immune responses and affect host-pathogen interactions in aquatic species, climate change is changing the health scene of aquaculture. Rising frequency and intensity of temperature swings, ocean acidification, and salinity changes are upsetting physiological equilibrium and increasing farmed fish and shellfish susceptibility to infectious illnesses. These developments compromise the output of aquaculture and the sustainability of world seafood supply chains. The complexity of climate-disease connections requires a thorough knowledge of microbial dynamics, ecology, and physiological processes under evolving environmental conditions.

The future of humanity depends critically on aquaculture systems being more robust. Stress-tolerant and disease-resistant species breeding, real-time environmental monitoring, and ecosystem-based methodologies such as integrated multi-trophic aquaculture (IMTA) help to mitigate climate-related consequences using adaptive strategies. Early warning systems and better disease surveillance are vital to prevent major outbreaks. Similarly, creating climate-smart aquaculture models requires multidisciplinary research, creative policy, and cooperation among several stakeholders. Besides lowering susceptibility, implementing such proactive and sustainable methods would ensure aquaculture can keep supplying food and income even as the world warms. Aquaculture's future rests on strategic adaptation, scientific creativity, and a worldwide dedication to environmental care.

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