

Communication And Predictive Modeling to Bridge Climate Knowledge Gaps in Aquaculture

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Abstract

Global warming and its influence on climate systems have emerged as critical threats to environmental stability and global development. As highlighted by the Intergovernmental Panel on Climate Change (IPCC), the increasing dependence on carbon-based economies has significantly accelerated climate change. By the end of the 21st century, global temperatures are projected to rise between 1.8°C and 6.0°C, with tropical deltaic areas facing particularly severe consequences. Such regions, which serve as major centres for aquaculture, are highly vulnerable to sea-level rise, saltwater intrusion, and declining freshwater availability. In tropical zones, aquaculture systems such as inland cage cultures may experience disruptions due to extreme weather events, reduced water quality, and seasonal imbalances, leading to oxygen depletion, fish mortality, and reduced production. This study examines how climate change affects aquaculture systems, particularly small-scale farmers, and explores adaptive strategies to enhance resilience. A delay differential equation-based mathematical model is developed to simulate the time-lagged effects of temperature, salinity, and feeding strategies on fish biomass, providing insights into adaptive and cost-effective management. Beyond technology, the study underscores the importance of communication strategies, including mass media outreach, participatory platforms, and targeted awareness campaigns, to bridge knowledge gaps, re-engage youth, and promote climate-smart aquaculture practices. By combining predictive modelling with traditional ecological knowledge and effective communication networks, the study offers a pathway towards climate-resilient, socially inclusive, and sustainable aquaculture systems aligned with the Sustainable Development Goals.

Key Words: Adaptive measures; Aquaculture; Climate change; Saline water intrusion; Socio-economic approaches; Traditional practices and communication

INTRODUCTION

The world is looking for ideal solutions to ensure a healthy environment and to provide basic requirements for the survival of the human population. The need of the hour is a shift from conventional energy, biodiversity conservation, and innovation in technology to mitigate global health problems, along with the extensive use of biotechnology in agriculture, forestry, aquaculture, and other animal resources to meet food requirements. Scientists have warned that the current rate of biodiversity loss is much greater than the pace of climate change (Shivanna, 2022). It has therefore become urgent to conserve nature from the harmful impacts of unsustainable human activities driven by overexploitation and lack of awareness.

Aquaculture, particularly in tropical and deltaic regions, has long relied on traditional practices passed down through generations (Costa-Pierce 2022). These practices, rooted in local ecological knowledge, have supported sustainable fish farming and community livelihoods. However, they are increasingly being discontinued (Aram, et al., 2014). A major reason is the lack of involvement of younger generations from farming families, who often view agriculture and aquaculture as economically uncertain or socially undervalued compared to other professions. This generational gap contributes to the gradual elimination of traditional methods, leaving many small-scale farmers vulnerable to the increasing pressures of climate change.

In this context, communication strategies and capacity building become significant role. Strengthening farmer engagement, especially among youth, through knowledge-sharing platforms and participatory approaches can help revive and adapt traditional aquaculture practices. At the same time, integrating these methods with modern tools such as predictive modeling offers new opportunities. Predictive models provide insights into temperature, salinity, and feeding responses under climate stress, while traditional practices ensure ecological sustainability and cultural continuity. Together, this combination can enhance resilience, support small-scale farmers, and promote sustainable development in vulnerable regions.

GLOBAL WARMING

Global warming is the term used to describe the current increase in the Earth's average temperature. '*Climate change*' refers not only to global changes in temperature but also changes in wind, precipitation, the length of seasons as well as the strength and frequency of extreme weather events like droughts and floods. Climate is a system consisting of the atmosphere, hydrosphere, lithosphere, cryosphere and biosphere.

CLIMATE CHANGE

Beyond rising temperatures, climate change brings unpredictable rainfall, cyclones, floods, heatwaves, and sea-level rise, with tropical and deltaic regions projected to face the most severe consequences (IPCC, 2021). For aquaculture, these events can degrade water quality, reduce oxygen levels, and increase the risk of disease, placing small-scale farmers and their livelihoods at significant risk.

Climate change is increasingly affecting food production. According to the National Fisheries Development Board (NFDB, 2020), fisheries and aquaculture contributed approximately 7.28% to India's agricultural Gross Value Added (GVA), highlighting their critical role in the nation's food security.

The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability.” Rising global temperatures are expected to raise sea levels, alter precipitation patterns, and affect ecosystems in profound ways (Pandey, 2005; Rao et al., 2008). Since preindustrial times, increasing greenhouse gas (GHG) emissions from human activities have significantly raised atmospheric GHG concentrations. The Intergovernmental Panel on Climate Change (IPCC, 2007) projects widespread impacts across regions, particularly threatening the livelihoods of small-scale aquaculture farmers.

Climate change is posing a severe threat to all the ecosystems of the earth and this will affect fisheries and aquaculture as well in a variety of ways via ocean acidification, changes in sea temperature and circulation patterns, frequently and severity of extreme events and sea-level rise. This brings many associated ecological changes in the aquaculture systems, viz. salinity intrusion in the further upstream of rivers, changes in monsoonal patterns and occurrence of severe extreme weather events such as cyclones and unusual floods. This effect of climate change will affect farming systems to a greater extent and is likely to threaten the food security and livelihood of millions of people in India (Swaminathan, 2012). The predictions of climate change in fisheries is well expected and hence the creation of adaptive measures to overcome the impact of climate change for better resilient aquaculture systems through capacity building in various levels of stakeholders is necessary (De Silva and Soto, 2009; Pedro and Soto, 2017).

Ocean plays a significant role in the global climate systems as well as a pertinent resource for humans on the coastal zones. The presently emerging anthropogenic climate change has a direct impact on the performance of global player “ocean” as well as on the risks in the coastal zones, ecosystems, living coastal marine fishery resources and human population (Harley *et. al.*, 2006).

Mean sea level is predicted to rise in the range of 30-50 centimeters. By the end of 21st century, the projected sea level rise will affect coastal areas with large population. This will damage the coastal ecosystems such as mangroves and salt marshes, fish stocks and aquaculture. Mangroves and other coastal vegetation defend the shore from natural disasters such as tsunamis and storm surges which can damage fish ponds and other coastal infrastructure and may become more frequent and intense under climate change. A number of studies have identified possible adaption strategies for mangrove systems that include raising awareness of the importance of these areas among local communities and leaders, minimizing stress unrelated to climate,

maintaining ecosystem connectivity, coastal planning, livelihood, and restoring coastal ecosystems (Muralidhar & Vijayan, 2015).

Higher sea levels may make groundwater more saline, harming fresh water fisheries, aquaculture and agriculture. Increased inland groundwater salinity has been observed in recent decades around the world. Along with the negative consequences, there may be benefits in the form of increased areas suitable for brackishwater aquaculture of high value species. This situation demonstrates the advantage of opportunities in aquaculture in diversifying people's livelihoods.

Coastal planning and management are constrained largely by lack of information, data and analysis about the interaction between development activity and the involvement of fisherfolk people. Development activities are agents of change. Development actions without considering locals lead to disasters.

Human Causes of Climate Change

Human-induced activities such as fossil fuel combustion, gas flaring, coal dependence, unsustainable land use, and deforestation have sharply raised greenhouse gas concentrations in the atmosphere. The resulting global warming, driven by the intensified greenhouse effect, poses severe risks to aquaculture—a sector vital for food security. Scientific consensus affirms that rapid industrial growth is the main driver of current climate change, with carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and chlorofluorocarbons (CFCs) as the leading anthropogenic gases behind this trend (Fig. 1).

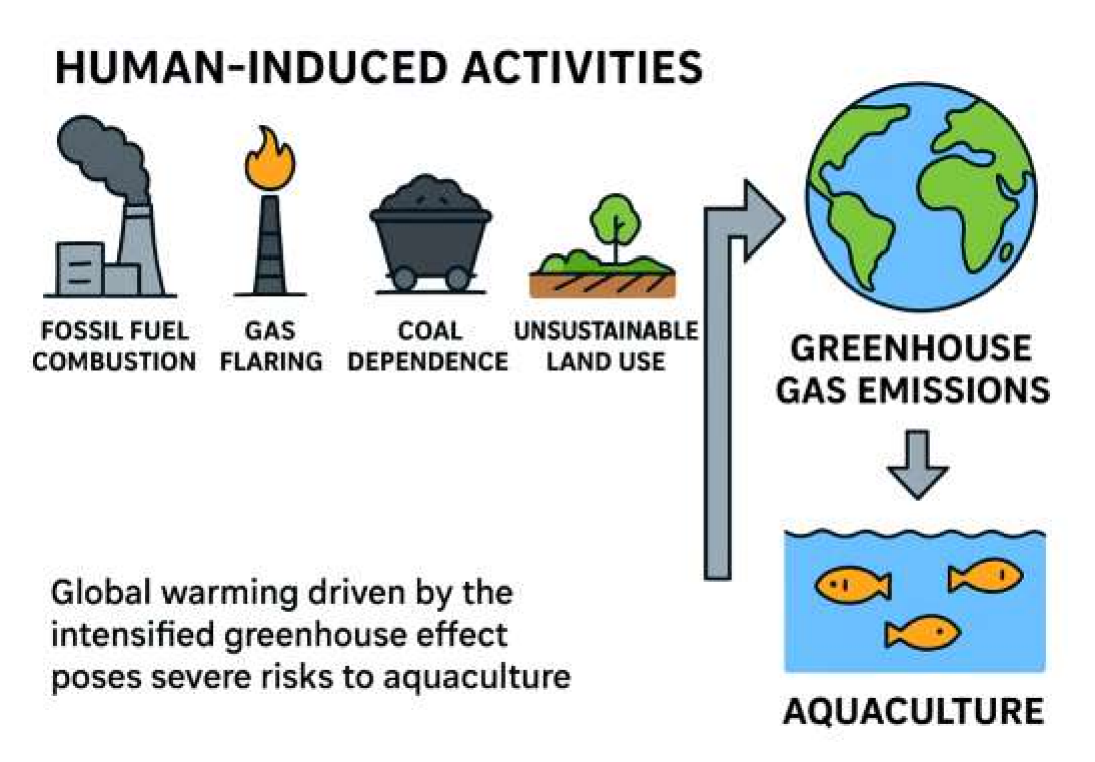


Figure 1. Human activities contribute to greenhouse gas emissions, leading to global warming and impacting aquaculture

Given these challenges, it becomes essential to study aquaculture, as the sector is highly sensitive to climate change and other human-induced pressures. Rising temperatures, altered rainfall patterns, and increased greenhouse gas emissions directly affect water quality, fish health, and overall productivity. Since aquaculture contributes significantly to global food security and rural livelihoods, understanding its vulnerabilities and developing adaptive strategies are critical for sustaining both nutrition and income for millions of people (Maulu et al., 2021).

AQUACULTURE

In India, capture fisheries have reached a stagnation point, making aquaculture the primary driver of future fish production (Lakra & Gopalakrishnan, 2021). At the same time, compared to agriculture, aquaculture

has recently emerged as a booming sector among youngsters. It has been observed that due to the lure of rapid economic gains, many young people are venturing into aquaculture without adequate awareness or training. For instance, a youngster from Coimbatore, Tamil Nadu, reported that he, along with a group of friends, initiated *freshwater* aquaculture with the expectation of tapping into the potential fish market in the north-western region of the state. However, owing to the lack of financial assistance from the government and limited awareness, the group was unsuccessful in sustaining the venture.

Globally, however, aquaculture is recognised as the fastest-growing food-producing sector, expanding at nearly 8–9% annually over the past two decades. At present, it contributes almost half of the fish consumed worldwide and provides direct and indirect livelihoods to millions of people (FAO, 2016). Nevertheless, certain regions in India continue to face challenges in fully realising the potential of aquaculture.

However, while some parts of India continue to struggle with getting awareness, financial support, and sustainability in aquaculture ventures, the global scenario presents a contrasting picture. Globally, aquaculture is the fastest-growing food-producing sector, expanding at nearly 8–9% annually over the past two decades. Today, it contributes almost half of the fish consumed worldwide and provides direct and indirect livelihoods to millions of people (FAO, 2016).

Aquaculture plays a critical role in ensuring nutritional security and supporting rural economies. However, climate change threatens its sustainability. Rising temperatures, shifting rainfall patterns, extreme weather events, and declining water quality disrupt aquatic ecosystems and affect fish growth, health, and productivity. These changes also increase the risk of disease outbreaks by weakening host resistance and altering host–pathogen interactions (Anon, 2016).

Given that aquaculture is concentrated in tropical and subtropical regions, particularly in Asia, the sector is especially vulnerable to climate-related impacts. Adaptive measures—such as improved farm site selection, resilient technologies for marine cage culture, and sustainable management of inland waters—are essential to mitigate risks.

As global demand for fish continues to rise, aquaculture will remain central to food security and livelihoods. Strengthening its resilience to climate change is therefore not just a sectoral need but a critical priority for sustainable development.

INLAND AQUACULTURE – FRESHWATER POND SYSTEMS

In tropical and subtropical regions, aquaculture is dominated by freshwater finfish farming in shallow ponds, which range from small household units to several hectares. Pond water temperature is influenced by air temperature, solar radiation, wind, and turbidity. Although local conditions may buffer some effects of rising global temperatures, climate change is expected to alter rainfall, evaporation, and water availability, posing challenges to the sustainability of pond-based aquaculture (IPCC, 2021).

In Asia, inland aquaculture often relies on non-native species, raising risks of accidental escapes during extreme climate events that can disturb ecosystems and cause financial losses (FAO, 2022). Globally, aquaculture now supplies nearly half of fish consumed, as capture fisheries stagnate, and integrated systems such as fish–rice farming enhance food and income security (FAO, 2022). Yet rising water temperatures, declining water quality, and emerging pathogens threaten production, making it vital to promote climate-resilient species and adaptive practices (IPCC, 2022; Maulu et al., 2021).

CAGE CULTURE

Cage aquaculture has become an important component of global fish production, particularly where land and freshwater resources are limited. In Asia, inland cage culture provides an alternative livelihood for communities displaced by reservoir development, though it is mostly confined to low- to mid-value species. However, unregulated expansion often leads to fish kills, disease outbreaks, and reduced profits due to overstocking and poor ecosystem management. Subsistence river-based cage farming, practiced by rural communities, remains vulnerable to declining wild seed stocks and climate variability. Promoting sustainable cage culture practices is essential not only for environmental health but also for securing stable rural livelihoods.

BRACKISHWATER AQUACULTURE

Brackishwater aquaculture especially shrimp and finfish farming in deltaic areas—has grown rapidly in Asia, South America, and the Caribbean, creating significant employment and export earnings. For example, catfish culture in Viet Nam and rohu farming in Myanmar have provided both food and income security.

However, sea-level rise and salinity intrusion threaten freshwater aquaculture, while the costs of shifting to salinity-tolerant species or relocating farms could strain communities dependent on this sector. Adaptive planning is therefore critical to ensure that brackishwater aquaculture continues to support sustainable livelihoods without leading to widespread pond abandonment or ecological damage.

MARICULTURE/ COASTAL AQUACULTURE

Mariculture in coastal waters focuses on high-value species such as seabass, groupers, molluscs, and seaweeds. These activities are increasingly promoted for their eco-friendly nature and potential for carbon sequestration, while also diversifying rural incomes in coastal regions. Yet in India, only a fraction of the available area is utilized despite rising demand for cultured seafood. Climate change-induced habitat changes, such as shifts in mangroves and coastal ecosystems, may alter species availability and production potential. Sustainable mariculture development, therefore, has the dual role of supporting coastal food supply chains and strengthening the livelihoods of artisanal and small-scale fishers.

Thus, while climate change poses serious threats to aquaculture production systems, it also highlights the urgent need for adaptation strategies that safeguard both ecosystem integrity and the livelihoods of communities dependent on aquaculture.

Climate Change Impacts on Aquaculture

Climate change affects aquaculture both directly and indirectly through shifts in water availability, temperature, salinity, and the frequency of extreme weather events. These changes threaten not only production systems but also the livelihoods of millions of people dependent on aquaculture.

Rising air and water temperatures influence pond aquaculture by altering solar radiation, evaporation, and water quality, often triggering algal blooms and red tides. Similarly, sea-level rise and saline water intrusion affect freshwater farming in deltaic areas, while damaging critical habitats such as mangroves that serve as nursery grounds for fish and shellfish. Extreme weather events—including floods, typhoons, and cyclones—destroy cage culture installations and lead to massive stock losses, reducing farm incomes and food availability (Soto et al., 2001). Decreased water availability in major rivers and lakes further disrupts fish spawning and seed supply, particularly in Asia and Africa (Goswami et al., 2006).

The Asia-Pacific region remains especially vulnerable due to its geographic exposure and reliance on aquaculture as a livelihood source. Climate change will likely force shifts in farm locations, adoption of salinity-tolerant species, and improved farming techniques. However, such adjustments carry economic costs and risks for smallholders. Moreover, reduced availability of fishmeal and fish oil for aquafeeds may constrain carnivorous finfish culture in temperate regions.

Despite these challenges, aquaculture remains less energy-intensive than many terrestrial food production systems and can contribute to carbon sequestration. With appropriate adaptation strategies—such as improved farm management, resilient species selection, and community-based planning—aquaculture can continue to secure food supplies while sustaining rural livelihoods under changing climatic conditions.

Environmental-climatic distribution of aquaculture

Aquaculture takes place in three main environments—freshwater, marine, and brackish water—across tropical, sub-tropical, and temperate climatic zones.

Changes in monsoonal patterns and climatic events

In recent decades, extreme weather events such as cyclones and floods have become more frequent, particularly in tropical and sub-tropical Asia. These events damage aquaculture facilities, cause stock losses, and facilitate the spread of diseases.

Influence of climate variability on aquaculture

Climate change affects aquaculture in both direct and indirect ways, though not all factors exert equal influence. Production is concentrated in specific climatic regions with well-defined practices (Yazdi and Shakouri, 2010). Historically, aquaculture expansion was shaped by cultural traditions of “living with water” and ethnic practices of fish farming. However, climate variability now also drives growth in some areas, where aquaculture itself offers adaptation opportunities for sectors such as coastal agriculture.

The impacts are rarely due to a single factor but result from interlinked processes (Phillips and Ramirez, 2018; Gubbins et al., 2013). Key elements projected by the IPCC (2007) include:

- **Global warming:** Planetary temperature may rise by 1.1–3 °C this century.

- **Sea-level rise:** Oceans could rise by 10–100 cm, due to thermal expansion (10–43 cm) and glacial melt (~23 cm), affecting deltaic regions through saline intrusion and biotic shifts.
- **Monsoon variability and extreme events:** Increased floods, altered rainfall, and greater storm intensity.
- **Water stress:** Freshwater availability in large river basins of Central, South, East, and Southeast Asia is projected to decline; Africa may see 75–250 million people under water stress.
- **Hydrological changes in inland waters:** Warming may intensify eutrophication, reducing food quality and availability, thereby affecting cage and pen culture in lakes and rivers.

Sea-level rise and saline intrusion

Sea-level rise linked with global warming, poses a serious threat to coastal aquaculture. In India, shrimp farming in the Sundarbans and Krishna–Godavari delta regions is highly vulnerable to saline intrusion and flooding. Saline water ingress not only reduces freshwater availability but also alters soil quality, damages pond infrastructure, and increases the risk of disease outbreaks. For example, studies from the Indian Sundarbans have shown that rising sea levels and saltwater intrusion have led to reduced freshwater aquaculture potential, forcing farmers to shift towards brackish water shrimp culture (Hazra et al., 2002; Mohanty et al., 2010). Such shifts often increase production costs and socio-economic risks for smallholders. Therefore, it can be said that *climate change (through sea-level rise) is pushing Indian aquaculture away from freshwater species towards brackish-water shrimp, but this shift is costly and risky for small farmers.*

Apart from coastal and deltaic regions, aquaculture in inland freshwater systems also faces serious risks due to climate-induced changes in rainfall and water availability.

Water stress and freshwater availability

Water stress is a major challenge for aquaculture, particularly in inland and river-based systems. Declining rainfall, reduced river flows, and over-extraction of groundwater have constrained freshwater availability for fishponds and hatcheries. In India, decreased flow in the Cauvery and Krishna river basins has disrupted carp and catfish farming, reducing seed production and fish yields (Kumar et al., 2018). Similarly, reduced water levels in tanks and reservoirs of Tamil Nadu and Karnataka have forced farmers to shorten culture cycles or shift to low-water requiring species. Such water scarcity, compounded by rising demand from agriculture and urban sectors, threatens the long-term sustainability of inland aquaculture in South Asia.

While water scarcity threatens inland aquaculture gradually through reduced resource availability, extreme climatic events pose sudden and often devastating shocks to aquaculture systems, particularly in coastal states of India.

While water scarcity gradually undermines inland aquaculture, the vulnerability of the sector is further intensified by extreme climatic events. The frequency and impact of such events are not only linked to climate variability but also aggravated by rapid, and often unsustainable, economic development—such as unplanned coastal expansion and inadequate disaster preparedness—that leave aquaculture systems exposed to sudden shocks.

Extreme weather events

Cyclones, floods, and heatwaves increasingly disrupt aquaculture by damaging ponds, cages, and hatcheries, resulting in massive stock losses and the spread of diseases. In India, Cyclone Phailin (2013) caused extensive damage to shrimp farms and hatcheries along the Odisha coast, with estimated losses running into hundreds of crores (Rath et al., 2015). More recently, Cyclone Amphan (2020) devastated aquaculture in West Bengal's Sundarbans, breaching embankments, flooding ponds with saline water, and displacing thousands of smallholder farmers (Chakraborty et al., 2021). These extreme events underline the urgent need for climate-resilient infrastructure and sustainable coastal planning to reduce aquaculture's vulnerability.

Other ingredients used in aquaculture: such as soybean meals and corn meals for the production of bio-fuel instead of usual feed production results to more economic and social challenges, especially in the aquaculture subsector.

Disease emergence and livelihoods

Climate-induced changes in temperature, salinity, and rainfall patterns increase the risk of diseases such as White Spot Syndrome Virus in shrimp and Epizootic Ulcerative Syndrome in freshwater fish (Mohan & Bhatta, 2002; Kumar et al., 2018). These outbreaks cause heavy stock losses, raising production costs and

reducing incomes. For small-scale farmers, such shocks threaten household food security and widen inequalities, undermining progress towards Sustainable Development Goals (SDGs), particularly poverty reduction and decent livelihoods. Given these livelihood losses and rising inequality, corrective strategies are essential to make aquaculture climate-resilient and aligned with SDG goals.

CORRECTIVE AND ADAPTIVE STRATEGIES

Given the livelihood shocks caused by climate-driven diseases and extreme events, corrective strategies are essential to strengthen aquaculture resilience and reduce inequalities. Species and system diversification, such as shifting to salinity-tolerant tilapia, mud crab, or seabass, has been shown to lower risks and aid recovery in cyclone-affected regions of Odisha (Chhotray, 2022; Government of Odisha, 2013). Climate-smart technologies like Biofloc and Recirculatory Aquaculture System (RAS) reduce water dependency and improve biosecurity, thereby supporting smallholders; these are now being promoted under national training programmes (Times of India, 2025; Kumar et al., 2025). At the community level, capacity building and cooperative planning improve adaptation, while aquaculture insurance schemes—though currently underutilised—offer potential to cushion losses from floods and disease outbreaks (Mongabay-India, 2024). Ecosystem-based approaches, including mangrove restoration in coastal belts, not only buffer storm surges but also secure grounds vital for shrimp and finfish culture (PreventionWeb, 2022). Collectively, these strategies demonstrate how climate-resilient aquaculture can safeguard livelihoods, narrow inequalities, and contribute to Sustainable Development Goals on poverty reduction, food security, and sustainable ecosystems.

The adoption of these corrective and adaptive measures has significant implications for aquaculture sustainability. By improving resilience, reducing livelihood inequalities, and enhancing ecosystem services, such strategies can help align aquaculture development with the Sustainable Development Goals (Akash & Arul Aram, 2022).



Figure 2: Adaptation and mitigation strategies

ADAPTATION AND MITIGATION AS CORRECTIVE STRATEGIES

These strategies also reflect broader pathways for adaptation and mitigation under climate change. Adaptation includes farm-level actions like diversifying species, adopting Biofloc and RAS, and strengthening capacity through training and farmer cooperatives. Insurance can further improve adaptive capacity by protecting smallholders from sudden losses.

Mitigation focuses on lowering environmental impacts. For example, Biofloc systems recycle nutrients and reduce waste, solar-powered aeration cuts dependence on fossil fuels, and mangrove restoration not only shields coastlines but also stores carbon. Together, these measures allow aquaculture to both adapt to climate variability and reduce its ecological footprint, ensuring a more sustainable future for local communities.

Mitigation strategies include:

Forest conservation measures that include the prohibition of deforestation encouraging afforestation and reforestation measures to curtail the emission of green-house gases to the atmosphere

1. Education as a means to create awareness to the citizens at the local, state and national levels
2. Adopting measures and programs to reduce the emission of these gases to the atmosphere by prohibiting the indiscriminate testing of both nuclear and atomic bombs
3. Risk reduction initiatives seeking to address vulnerabilities through early warning systems timely seasonal weather forecasts, market information systems and disaster recovery programs.

Adaptive strategies include:

4. Integrating climate issues into economic planning and management at both the national, state and local levels
5. Mobilizing investment through international technology transfer to facilitate investment into private public power participation for efficiency and reliability and in the petroleum industry to harness natural gas for both domestic and fossil fuels for generators
6. Discouraging population growth for effective economic and social planning. This will reduce pressure on the available natural resources and also competition for space and survival that encourages conflicts for land, deforestation etc.

While these strategies highlight promising directions for climate-resilient aquaculture, their effectiveness depends on how well they can be anticipated, quantified, and optimized under uncertain climatic conditions. To bridge this gap, this current study introduces a mathematical modelling framework that integrates delayed biological and environmental responses with real-world management actions.

Introduction to the Modelling Framework

Mathematical modelling provides a structured way to analyse complex bio-environmental systems, where responses often occur with delays rather than instantly. Such time lags—seen in growth, stress adaptation, or environmental shifts—are best represented using delay differential equations (DDEs), which account for both present and past system states (s, Jin, & Riedel-Kruse, 2021).

This study develops a framework that combines delayed biological and environmental responses with management actions such as feeding, aeration, and water exchange. By linking system dynamics with practical controls, the model supports scenario testing and decision-making under variable and uncertain conditions. Aquaculture systems respond to environmental and biological stressors with delays rather than immediate changes. Capturing these lags is essential for realistic simulations and effective management planning. Mathematical modelling provides a structured framework to achieve this, and delay differential equations (DDEs) are particularly suited for representing systems where past states influence present dynamics (Glass, Jin, & Riedel-Kruse, 2021).

Two key delays are considered:

- **Biological delay (τ):** the time required for fish to physiologically respond to density changes, such as growth inhibition from overcrowding.
- **Environmental delay (δ):** the lagged effects of climatic factors such as temperature and salinity on carrying capacity and mortality.

The proposed DDE model describes biomass dynamics while incorporating **management controls**—feeding, aeration, or other mitigation measures—that reflect real aquaculture practices. By integrating delayed responses with control strategies, the framework simulates realistic system behaviour under climate uncertainty and provides a basis for optimizing trade-offs between yield and resource use.

This approach offers a practical decision-support tool to help aquaculture stakeholders anticipate long-term climate impacts and adapt management strategies accordingly.

Notation and State Variables

To construct the mathematical model describing aquaculture dynamics under climate influence, we define the key variables, parameters, and control functions involved. These notations serve as the foundation for the formulation of the delay differential equation and the associated optimization framework.

State Variable

- $N(t)$: Represents the biomass of the aquatic species (e.g., fish) at time t , typically measured in kilograms (kg). This is the primary state variable whose evolution we aim to simulate and optimize.

Control Variables

- $F(t)$: Denotes the feeding effort or feed input at time t . This control variable represents the quantity of feed supplied to the fish population and directly influences the growth rate.
- $u(t)$: Denotes the mitigation effort at time t , such as actions taken to reduce environmental stress (e.g., water aeration, temperature control, or relocation). This variable helps to counteract the adverse effects of temperature and salinity deviations on fish health.

Environmental Inputs

- $T(t)$: Refers to the ambient water temperature at time t , which affects metabolic rate, growth, and mortality.
- $S(t)$: Refers to the salinity of the water at time t , another environmental factor influencing fish physiology and survival.

Time Delays

- τ : The biological delay, representing the time lag between changes in biomass density and the resulting effect on growth (e.g., due to competition or limited resources).
- δ : The environmental delay, representing the time lag between changes in environmental conditions and their impact on carrying capacity or mortality (e.g., thermal stress effects may take days to manifest).

Model Parameters

- r : Intrinsic growth rate of the fish species.
 - $K(T, S)$: Time-dependent carrying capacity of the system, influenced by temperature and salinity.
 - $m(T, S)$: Mortality rate, also dependent on environmental factors.
 - α : Efficiency of feed conversion into biomass.
 - ϵ : Fractional reduction in feed efficiency due to environmental stress.
- These variables and parameters together define the dynamic behaviour of the aquaculture system, allowing us to formulate and analyse how both natural processes and management interventions influence biomass production under climate-driven conditions.

Delay Differential Equation Model

The core of the modeling framework is a nonlinear delay differential equation (DDE) that describes how the biomass of a cultured aquatic species evolves over time, under the influence of both environmental conditions and management controls. This equation incorporates time delays to reflect the fact that biological and environmental responses are not instantaneous but unfold over a period.

The general form of the model is given by:

$$\frac{dN(t)}{dt} = rN(t) \left(1 - \frac{N(t-\tau)}{K(T(t-\delta), S(t-\delta))}\right) - m(T(t), S(t))N(t) + \alpha F(t)(1 - \epsilon u(t))$$

Explanation of Terms:

- The term $rN(t) \left(1 - \frac{N(t-\tau)}{K(T(t-\delta), S(t-\delta))}\right)$ represents logistic growth with a delayed density effect. The fish population grows at a rate proportional to its current size $N(t)$, but the growth is constrained by the carrying capacity K , which itself is influenced by past environmental conditions (temperature and salinity) and past population density (with delay τ).
- The mortality term $m(T(t), S(t))N(t)$ models environment-dependent losses, where the mortality rate increases with deviation from optimal temperature and salinity values.
- The last term, $\alpha F(t)(1 - \epsilon u(t))$, captures growth induced by feeding. Feed is converted into biomass at efficiency α , and its effectiveness can be partially reduced by adverse environmental conditions. However, this negative effect is moderated by mitigation actions $u(t)$, such as aeration or other climate adaptation efforts.

Nature of the Delay Terms:

- The biological delay τ captures how growth at time t depends on the population size at a previous time $t - \tau t$. This is a realistic assumption in fish physiology, where the effects of density or past feeding are not immediate.
- The environmental delay δ reflects the lag in the ecosystem's response to past temperature and salinity conditions. For instance, a sudden drop in temperature may take several hours or days to cause a measurable increase in stress-induced mortality or decline in carrying capacity. This delay-based formulation allows for more accurate predictions in scenarios where climate-induced fluctuations do not result in instantaneous biological changes. By including these delays, the model captures the memory effect that is often observed in real-world aquaculture systems.

Carrying Capacity Function

In ecological models, the carrying capacity represents the maximum sustainable biomass that the environment can support at any given time. However, in aquaculture systems exposed to climate change, this capacity is not constant—it varies dynamically with environmental factors, particularly temperature and salinity. These two variables directly affect water quality, oxygen levels, nutrient cycles, and the physiological tolerance of aquatic organisms.

To reflect these influences, the carrying capacity is modeled as a temperature- and salinity-dependent function, given by:

$$K(T, S) = K_0 \cdot \exp \left(-\beta_1(T - T_{\text{opt}})^2 - \beta_2(S - S_{\text{opt}})^2 \right)$$

Explanation of Parameters:

- K_0 : The maximum carrying capacity under optimal environmental conditions (i.e., when $T = T_{\text{opt}}$ and $S = S_{\text{opt}}$).
- T : Current water temperature.
- S : Current salinity level.
- $T_{\text{opt}}, S_{\text{opt}}$: The optimal temperature and salinity values for the given aquaculture species.
- β_1, β_2 : Non-negative sensitivity coefficients that determine how strongly the carrying capacity declines as temperature or salinity deviates from their respective optimal values.

Functional Behavior:

This formulation assumes a Gaussian-shaped response, where the carrying capacity is highest when environmental conditions are ideal, and declines symmetrically as conditions deviate from the optimum. The exponential decay ensures that even moderate environmental stress can reduce the system's ability to sustain biomass, thereby reflecting real-world vulnerabilities.

The inclusion of this function in the model ensures that population growth is not only density-regulated but also climate-sensitive, enabling more realistic projections of fish production under fluctuating environmental conditions.

Mortality Function

In aquaculture systems, the mortality rate of aquatic species is highly influenced by environmental stressors such as temperature and salinity. While extreme values of these factors can cause immediate death, even moderate deviations from optimal ranges can gradually increase physiological stress, reduce immunity, and lead to delayed mortality.

To capture these effects, the mortality rate is modeled as a quadratic function of temperature and salinity deviations from their species-specific optimal levels:

$$m(T, S) = m_0 + \gamma_1(T - T_{\text{opt}})^2 + \gamma_2(S - S_{\text{opt}})^2$$

Explanation of Parameters:

- $m(T, S)$: Mortality rate at given temperature T and salinity S .

- m_0 : Baseline mortality rate under optimal conditions, representing natural or unavoidable losses in the absence of environmental stress.
- γ_1, γ_2 : Sensitivity coefficients that determine how rapidly mortality increases as temperature and salinity deviate from their optimal values.
- $T_{\text{opt}}, S_{\text{opt}}$: Optimal environmental conditions for temperature and salinity.

Interpretation:

This functional form assumes that mortality increases nonlinearly as environmental conditions move away from the optimum. The quadratic structure ensures that both under- and over-shooting the ideal temperature or salinity can be harmful, which is consistent with biological observations in aquaculture. For example, if T is much higher or lower than T_{opt} , the value of $(T - T_{\text{opt}})^2$ becomes large, thereby increasing mortality. Similarly, salinity outside the species' tolerance range contributes to additional mortality pressure. This mortality function enhances the realism of the model by ensuring that climatic extremes have immediate and compounding effects on population survival, and it interacts directly with the biomass equation to shape overall system dynamics.

Objective Function for Optimization

In aquaculture management, achieving high productivity must be balanced with minimizing operational costs and mitigating the impact of environmental stress. To formalize this trade-off, we introduce an objective function that quantifies the overall performance of the system in economic and ecological terms. The optimization goal is to determine the optimal feeding rate and mitigation effort over a fixed time horizon such that the total cost is minimized while maintaining or increasing the biomass of the cultured species. The objective function is defined as:

$$J = \int_0^T [c_1 F(t)^2 + c_2 u(t)^2 - c_3 N(t)] dt$$

Explanation of Terms:

- J : The total cost functional to be minimized.
- T : The final time of the planning horizon.
- $F(t)$: Feed input at time t .
- $u(t)$: Mitigation effort (e.g., aeration, cooling, water treatment) at time t .
- $N(t)$: Biomass of the species at time t .
- c_1, c_2 : Positive weight parameters representing the economic cost associated with feeding and mitigation, respectively.
- c_3 : A positive benefit parameter associated with the value of biomass or harvest yield.

Objective and Interpretation:

- The term $c_1 F(t)^2$ represents the cost of feed, with a quadratic penalty to discourage excessive feeding beyond economically viable limits.
- The term $c_2 u(t)^2$ penalizes intensive mitigation, reflecting the cost and effort required to counteract environmental stress.
- The term $-c_3 N(t)$ provides a reward for maintaining or increasing biomass, emphasizing the economic value of a healthy and productive fish stock.

This objective function reflects the real-world trade-offs in aquaculture operations: higher feed and mitigation may enhance growth and survival, but they also increase costs. The optimization seeks a balance that leads to the most cost-effective production strategy under given environmental conditions and biological constraints. By minimizing J , we derive the control trajectories $F(t)$ and $u(t)$ that produce the best management outcomes over time.

Control Constraints

In practical aquaculture operations, the levels of feed input and mitigation efforts are not unlimited. Physical limitations, financial costs, and ecological thresholds impose realistic upper and lower bounds on the control

variables used to manage the system. Therefore, to ensure the feasibility and applicability of the optimization model, we incorporate control constraints that reflect operational limits. The constraints on the control variables are defined as follows:

$$0 \leq u(t) \leq 10 \leq F(t) \leq F_{\max}, \quad 0 \leq u(t) \leq 1$$

Explanation of Constraints:

- $F(t)$: Represents the feeding rate at time t . The lower bound of zero implies that feeding can be stopped entirely if necessary. The upper bound $F_{\max}$ represents the maximum allowable feed input, dictated by budget, storage capacity, or species-specific feeding tolerance.
- $u(t)$: Denotes the mitigation effort at time t , scaled between 0 and 1. A value of $u(t) = 0$ indicates no intervention (i.e., passive management), while $u(t) = 1$ represents the maximum feasible mitigation effort, such as full-scale aeration, shading, or water treatment.

Practical Justification:

These constraints make the optimization problem well-posed and realistic. They prevent the model from recommending impractical or biologically unsustainable control strategies, such as overfeeding or applying mitigation beyond technical capacity. In computational terms, these bounds also help guide the optimization algorithm within acceptable regions of the control space.

The control constraints are enforced throughout the optimization horizon and play a crucial role in shaping the trade-offs between biomass production, environmental adaptation, and cost minimization.

Initial Conditions and History

Unlike ordinary differential equations, delay differential equations (DDEs) require not only an initial value at a single time point but a full history function that defines the state of the system over a preceding time interval. This is because the system's evolution depends on past values due to the presence of time delays in both biological and environmental processes.

History Function Definition

To initialize the model, we specify the biomass function $N(t)$ for the time interval:

$$t \in [-\theta, 0], \quad \text{where } \theta = \max(\tau, \delta)$$

Here, θ represents the maximum delay in the system, ensuring that all delayed terms in the model are well-defined from time $t = 0$ onward.

Let: $N(t) = \phi(t)$, for $t \in [-\theta, 0]$ where $\phi(t)$ is a known, continuous, and biologically realistic function that describes the population biomass during the initial history period.

Choice of History Function

In practice, the history function $\phi(t)$ may be chosen in one of the following ways:

- As a constant: $\phi(t) = N_0$, representing a stable biomass prior to simulation.
- As a time-dependent curve: based on recorded field data or prior model simulations.
- As a step or ramp function: to simulate abrupt environmental or operational changes (e.g., stocking or harvesting events).

This historical biomass profile is essential to compute the delayed terms:

- $N(t - \tau)$: delayed population feedback
- $K(T(t - \delta), S(t - \delta))$: carrying capacity influenced by past climate
- $m(T(t), S(t))$: immediate mortality due to current environment

By accurately specifying the initial state and its delay-dependent history, the model can realistically capture the transient dynamics of aquaculture systems transitioning into a climate-influenced regime.

Simulation and Optimization

The implementation of the mathematical model requires numerical techniques capable of solving delay differential equations (DDEs) while also handling control optimization under practical constraints.

Numerical Simulation Approach

To simulate the dynamics of the biomass system governed by the DDE, we employ a modified Runge-Kutta (RK) method tailored for delay equations. Unlike classical ordinary differential equations (ODEs), the solution at a given time t in a DDE depends not only on the current state but also on past values. This requires maintaining and referencing the solution history over the interval $[t - \theta, t]$, where $\theta = \max(\tau, \delta)$ represents the maximum delay in the system.

The RK algorithm progresses by discretizing the time domain into small steps h , and at each step:

- It interpolates past values of the state $N(t - \tau)$, and environmental inputs $T(t - \delta)$, $S(t - \delta)$ as needed.
- It computes the right-hand side of the DDE using current and delayed terms.
- It updates the solution based on RK integration formulas and stores the state history for future access.

This method offers a good balance between computational efficiency and numerical accuracy, particularly for systems with nonlinear delayed feedback like the aquaculture model presented here.

Optimal Control Strategy

To determine effective management decisions over time, we formulate an optimal control problem where the objective is to minimize a cost functional that balances feeding and mitigation costs against biomass production benefits. The control variables—feed rate $F(t)$ and mitigation effort $u(t)$ —are discretized into piecewise constant segments across the simulation horizon, with updates every 5 days. This mirrors practical decision-making intervals in aquaculture operations.

The optimization algorithm used is the Limited-memory Broyden–Fletcher–Goldfarb–Shanno with Box constraints (L-BFGS-B) method, which is well-suited for nonlinear objectives and bounded controls. The algorithm searches for the optimal set of constant control values in each interval such that the total cost is minimized while biomass growth is sustained.

Simulation Results and Control Performance

The simulation-optimization process was conducted over a typical aquaculture cycle. The outcomes were as follows:

- Final biomass achieved: approximately 366.43 kg, indicating healthy growth under optimized feeding and mitigation schedules.
 - Net cost-benefit: the optimized strategy resulted in a minimized total cost of −31,505.04 units, reflecting both operational efficiency and effective climate adaptation.
 - Control behavior: feeding levels were higher in growth-favorable periods and reduced during stress phases, while mitigation efforts were selectively activated when environmental risks were predicted to be high.
- The results confirm that the delay-aware modeling approach, when combined with structured piecewise control and numerical optimization, can guide adaptive and economically viable management of aquaculture systems under climate variability.

RESULTS AND DISCUSSION

This section presents the outcomes of the Delay Differential Equation (DDE) model developed to analyse the dynamics of aquaculture biomass under climate-induced stress, subject to control strategies involving feed input and environmental mitigation. A Runge–Kutta-based numerical scheme was employed to solve the model equations, and simulations were conducted for a 100-day cultivation cycle. The results are analyzed both qualitatively and quantitatively through time series plots, control profiles, sensitivity curves, and heatmaps.

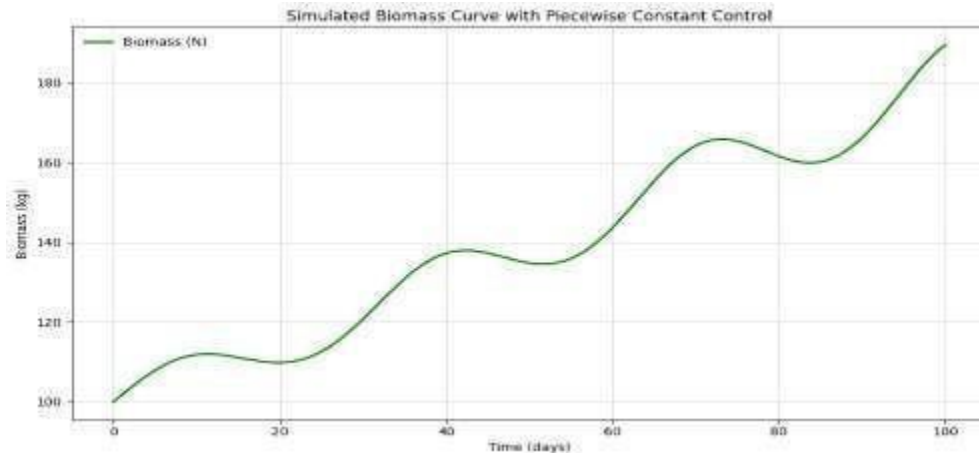


Figure 3: Simulated Biomass Curve with Piecewise Constant Control

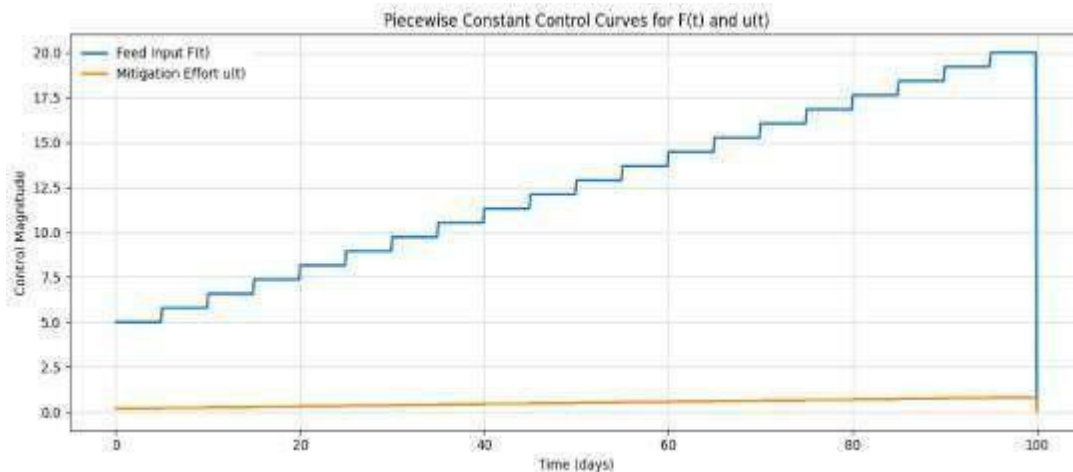


Figure 4: Piecewise Constant Control Curves for $F(t)$ and $u(t)$

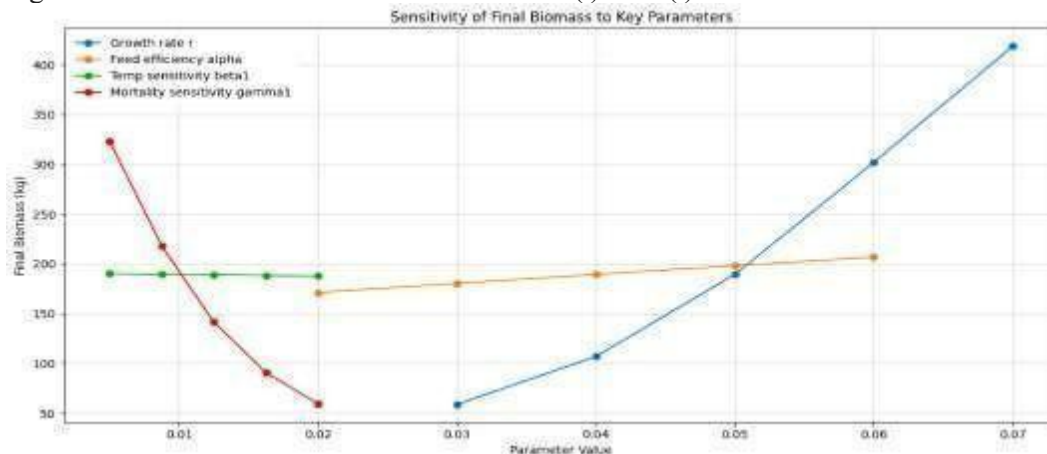


Figure 5: Sensitivity of Final Biomass to Key Parameters

BIOMASS EVOLUTION UNDER DELAYED DYNAMICS

The simulated biomass curve (Figure 4) demonstrates a non-monotonic but increasing trajectory, indicating that the aquaculture species responds favorably to the implemented control interventions even under fluctuating environmental conditions. Oscillations in the biomass trajectory are a direct consequence of the embedded delays—specifically, the biological delay in growth response and the environmental delay in stress effects. These lags capture realistic physiological and ecological responses to feed and temperature, offering more accurate insights than Ordinary Differential Equation (ODE) models.

Notably, the biomass grows from 100 kg to over 180 kg by the end of the simulation, despite periodic dips caused by environmental stress. The delay structure, combined with climate variability, induces a transient drop around days 40 and 80, yet the overall trend is positive, confirming the model's capacity to reflect adaptation under delayed climate effects.

Performance of Control Strategies

The piecewise constant control inputs $F(t)$ (feed) and $u(t)$ (mitigation effort), shown in (Figure 5), were designed to evolve over 5-day intervals. The increasing nature of both inputs reflects an adaptive response strategy, where feed quantity and environmental interventions intensify over time to counteract cumulative stress.

This control regime enables a smoother biomass build-up while avoiding instability or overfeeding that may arise from constant high-level input. The synchronization between increasing feed and mitigation ensures resource optimization while protecting the system from overexposure to salinity and temperature fluctuations.

Sensitivity Analysis of Key Parameters

To assess the robustness of the model and the influence of uncertain parameters, a one-at-a-time (OAT) sensitivity analysis was performed for four critical coefficients: growth rate (r), feed efficiency (α), temperature sensitivity (β_1), and temperature-dependent mortality sensitivity (γ_1).

- Growth rate (r) shows a strong positive correlation with final biomass, indicating that intrinsic growth mechanisms dominate the productivity landscape.
- Feed efficiency (α) positively affects biomass, though with diminishing returns, suggesting the importance of optimizing rather than maximizing feed.
- Temperature sensitivity (β_1) exhibits negligible influence within the tested range, reflecting the buffering effect of environmental control $u(t)$.
- Mortality sensitivity (γ_1) causes a steep decline in biomass with increasing values, highlighting that temperature-induced stress mortality is a critical vulnerability and must be mitigated through precision environmental management.

These trends (Figure 6) not only validate the biological relevance of the model but also identify sensitive levers for strategic intervention.

Heatmap Insights under Climate Perturbations

To visualize interactions between delay parameters and environmental shifts, a heatmap was generated to represent final biomass levels across a matrix of biological delays (τ), environmental delays (δ), and temperature shifts. The results reveal that shorter biological delays and prompt environmental responses yield higher final biomass. However, elevated temperatures (+2°C) significantly reduce biomass across all delay settings.

This underscores the importance of rapid intervention and temperature control technologies, such as aerators or shade structures, especially under future warming scenarios. The heatmap serves as a diagnostic tool to predict performance under various climate risk configurations.

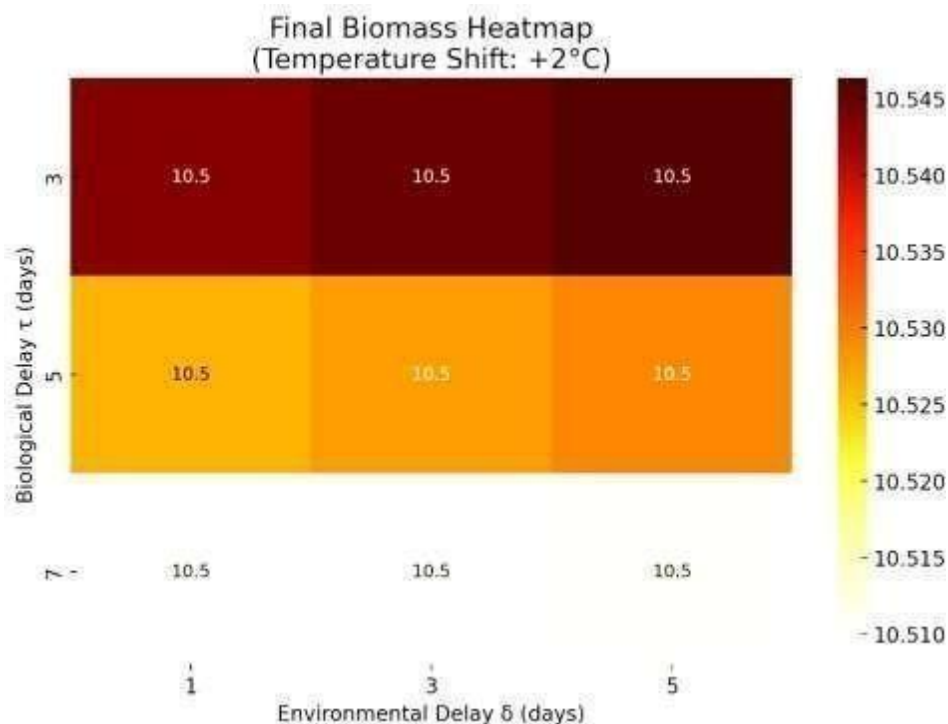


Figure 6: Final Biomass Heatmap

Model Utility and Practical Implications

Overall, the delay differential equation model effectively captures the time-lagged responses inherent to aquaculture systems under climate variability. The simulation results offer valuable insights into the timing and intensity of feeding and mitigation efforts. Moreover, the sensitivity and heatmap analyses provide a blueprint for decision-making under uncertainty, particularly in designing adaptive strategies for sustainable aquaculture.

From a practical perspective, this model can be integrated with real-time environmental monitoring systems to offer control recommendations and risk predictions. Furthermore, the framework can be extended to multi-species or spatially distributed farms, making it a scalable tool for precision aquaculture in a changing climate.

CONCLUSION

On analysing the study could be concluded that climate change is emerging as a significant threat to aquaculture, disrupting conventional farming systems and affecting the livelihoods of communities that rely on them. In India, aquaculture relies heavily on traditional knowledge and local ecological practices. However, there is a drastic reduction in the number of young people getting involved in farming today. This decline makes it harder to maintain sustainable practices amid changing climate conditions.

To address this, effective media outreach and communication strategies are crucial to raise awareness, inspire youth participation, and highlight the opportunities within modern, climate-resilient aquaculture.

This study emphasizes the need to combine traditional wisdom with modern scientific tools to build climate-resilient aquaculture systems. By developing a delay differential equation-based model, the study provides a practical approach to understanding how delayed environmental effects—particularly fluctuations in temperature and salinity—impact fish biomass over time.

The model enables farmers and stakeholders to make smarter decisions regarding feeding strategies and mitigation efforts. Through simulations and optimization, it demonstrates how adaptive control can enhance growth and reduce operational costs, even under climate stress. These insights are especially valuable for small-scale farmers, who often lack access to real-time climate planning tools.

In essence, climate change is hurting aquaculture, but adapting through the thoughtful integration of traditional practices and data-driven models offers a way forward. This approach not only strengthens

resilience but also holds the potential to re-engage younger generations by making aquaculture more efficient, economically viable, and aligned with modern sustainability goals.

To support informed decision-making in this evolving landscape, the present study has developed a delay differential equation-based mathematical model that captures the time-lagged effects of climate stressors on aquaculture productivity. By simulating biomass growth under varying control strategies and environmental conditions, the model provides valuable insights for designing adaptive, cost-effective, and resilient aquaculture systems in the face of climate uncertainty.

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Conflict of Interest: The authors declare that they have no conflicts of interest related to the content of this article.

Funding: The authors did not receive any funding from any agencies. All expenses were borne by the authors themselves.