Quest Journals
Journal of Research in Environmental and Earth Sciences
Volume 11 ~ Issue 3 (2025) pp: 45-61
ISSN(Online) :2348-2532
www.questjournals.org

Research Paper

The Impact of Climate Change on Aquaculture: Challenges and Adaptation Strategies. A Review

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Abstract
Climate change presents a significant and multifaceted threat to global aquaculture, a crucial source of food and livelihoods. This review synthesizes current knowledge on the direct and indirect impacts of climate change on aquaculture production, encompassing rising temperatures, sea-level rise, ocean acidification, water stress, and extreme weather events. These stressors profoundly affect aquatic species' growth, reproduction, health, and survival, with tropical and subtropical regions, particularly in Asia, facing heightened vulnerability. Indirectly, climate change disrupts feed supplies, alters biodiversity, and exacerbates disease prevalence. The review further examines the potential impacts of aquaculture on climate change and emphasizes the urgent need for robust mitigation and adaptation strategies. These strategies include optimizing nutrition, leveraging genetics and biotechnology, employing innovative management and engineering solutions, improving information systems, and strengthening governance frameworks. Enhancing climate forecasting, promoting sustainable practices, and fostering international policy alignment are crucial for building resilience and ensuring the long-term sustainability of the aquaculture sector in the face of evolving climatic challenges.

Keywords:* *Aquaculture; Climate change; Adaptation; Ocean acidification; Sustainable management

Received 17 Mar., 2025; Revised 28 Mar., 2025; Accepted 31 Mar., 2025

I. Introduction

Climate change is exerting profound impacts on the world's oceans, with far-reaching consequences for aquaculture, a vital source of food and income for millions of people globally. As the planet's temperature continues to rise, aquaculture systems are increasingly vulnerable to climate-related stressors, including ocean acidification, sea-level rise, and changes in water temperature and precipitation patterns. These changes are altering the delicate balance of aquatic ecosystems, affecting the growth, survival, and productivity of farmed species, and undermining the long-term sustainability of aquaculture operations. Furthermore, climate change is also impacting the livelihoods and food security of communities that depend on aquaculture, exacerbating existing social and economic vulnerabilities.

The global aquaculture industry is facing unprecedented challenges in maintaining production levels, managing disease outbreaks, and ensuring the quality and safety of farmed seafood. Climate change is also altering the distribution and prevalence of aquatic diseases, parasites, and pests, which can have devastating impacts on aquaculture operations. Moreover, the increasing frequency and severity of extreme weather events, such as hurricanes, typhoons, and floods, are damaging aquaculture infrastructure, disrupting supply chains, and threatening the livelihoods of aquaculture-dependent communities.

II. Aquaculture Production

Examining past trends in aquaculture production across different climate regimes can help identify regional vulnerabilities and opportunities for adaptation, ultimately informing strategies to enhance the resilience and sustainability of the industry. By analysing historical data on aquaculture production, climate variables, and environmental factors, the complex relationships between climate, environment, and aquaculture productivity can be understood and develop more effective measures to mitigate the impacts of climate change.

2.1 Climatic Distribution of Production

Global aquaculture production has exhibited distinct geographical patterns, with tropical and subtropical regions dominating production, accounting for over 50% of major cultured commodities (finfish, molluscs, crustaceans, and seaweeds) [1,2]. Notably, crustacean production was concentrated in tropical regions, accounting for approximately 70% of global production. In contrast, mollusc and seaweed culture in temperate regions declined over the past decade, now contributing around 10% to total global production [2].

2.2 Environmental – Climatic Distribution of Aquaculture

Aquaculture production is distributed across three environments (freshwater, marine, and brackish waters) and three climatic regimes (tropical, subtropical, and temperate). Analysis of production data from 1980 to 2005 reveals that, except for molluscs, most major aquaculture commodities (finfish, crustaceans, and seaweeds) are predominantly produced in tropical regions, followed by subtropical regions, and significantly less in temperate regions. Notably, finfish culture occurs mainly in freshwater, while crustaceans and molluscs are cultured in brackish and marine waters, respectively [2].

2.3 Climatic – National – Regional Distribution of Aquaculture

Analysis of 2005 data reveal that Asia dominates global aquaculture production, accounting for over 90% of the four major commodities (finfish, molluscs, crustaceans, and seaweeds) across tropical, subtropical, and temperate climatic regimes. This overwhelming concentration of production in Asia underscores the region's critical role in global aquaculture and highlights the need for targeted adaptive strategies to mitigate the impacts of climate change on Asian aquaculture, in order to ensure the long-term sustainability of this vital industry [2].

III. Impacts Of Climate Change on Aquaculture

Climate change is expected to impact aquaculture through various factors, including rising sea temperatures (up to 3°C by the end of this century) [3], sea level rise (10-100 cm) [3], changes in ocean productivity and circulation patterns [4,5,6], increased frequency of extreme weather events [3], and altered freshwater availability [3]. These changes will have far-reaching consequences for aquaculture, including impacts on food webs, habitat quality, and disease prevalence [7]. Additionally, climate-driven changes in water temperature, pH, and oxygen levels can alter the growth, survival, and reproduction of cultured species, leading to reduced productivity and increased vulnerability to disease and parasites. Furthermore, the increased frequency and severity of extreme weather events, such as hurricanes, floods, and droughts, can damage or destroy aquaculture infrastructure, leading to significant economic losses.

3.1 Rising Temperature

Rising temperatures due to climate change are expected to impact aquaculture production, particularly in coastal areas. Temperature plays a critical role in the growth and development of aquatic animals [8]. Fish, being poikilothermic, may particularly be sensitive to temperature variations resulting from climate change [9,10]. A 1.5°C rise in average global temperature is predicted to cause increased mortalities for most fish, especially cold-water species [11,12]. Temperature stress can affect fish growth, survival, and reproduction, leading to reduced productivity and increased vulnerability to disease. Additionally, rising ocean temperatures and consequential ocean acidification slowly weaken the ocean carbon sink capacity, giving rise to alterations in the hydrology and hydrography of water systems, and the occurrence of red tides [13]. These effects may lead to increased management costs and low productivity that threaten the economic and social sustainability of aquaculture production. Moreover, temperature variations can alter the distribution and abundance of nutrients, affecting the growth and survival of aquatic animals [14].

However, warmer temperatures may promote longer growing seasons, especially in temperate regions, and favour the production of warmer water species [15,16,17,18]. End-of-century model projections predict sea surface temperature increases ranging from 0.71 ± 0.45°C (RCP 4.5) to 2.73 ± 0.72°C (RCP 8.5) [19]. River water temperatures are projected to increase by 0.8−1.6°C by the end of the century (under the IPCC Special Report on Emission Scenarios B1−A2 scenario).

Temperature effects on aquaculture species can vary by biological process and life stage, introducing complexity in predicting outcomes [20,21]. While elevated temperatures may promote growth rates, increased variability and temporal extremes can act as stressors, increasing production risk [22]. Furthermore, temperature-driven changes in species distribution, behaviour, and physiology can lead to changes in disease dynamics, parasite-host interactions, and nutrient cycling, ultimately affecting aquaculture productivity and sustainability [23,24,25].

In addition, climate-driven temperature changes can lead to increased energy costs for aquaculture operations, particularly those that rely on cooling systems to maintain optimal water temperatures [16]. This can lead to increased production costs, reduced profitability, and decreased competitiveness in the global market.

On the other hand, warmer temperatures can also provide opportunities for aquaculture development in new regions, such as the Arctic [26], and facilitate the culture of new species. Advances in genetic improvements and molecular biology may also provide opportunities for aquaculture development, but may also threaten environmental sustainability if not properly managed [12,27].

3.1.1 Aerobic Capacity

Climate change is causing a decline in dissolved oxygen levels in ocean regions, exacerbating the effects of increased temperature on aquatic ectotherms [28]. As temperature rises, oxygen demand increases, constraining aquatic animals' aerobic capacity [29,30]. This can impact aquaculture practices, including stocking densities, feed intake, growth rates, and water usage [31]. Temperature affects aerobic capacity differently across species, with eurythermal species tolerating a wider temperature range than stenothermal species. Within aquaculture, positive or negative responses to temperature will depend on where the change occurs on the aerobic performance curve for a particular life stage or physiological process [32,33]. A temperature increase near the lower limit could be beneficial, while an increase near the upper limit will likely be detrimental. Environmental stressors, such as hypoxia and ocean acidification, can further reduce the temperature range of aerobic performance [34]. Some species, like Pangasius catfish, can tolerate hypoxia through air breathing, but may incur other costs [35,36].

3.1.2 Reproduction, Growth, and Development

Temperature affects reproductive performance in poikilotherms, influencing embryo survival, fecundity, spawning time, maturation rate, and sex ratio [37]. Elevated temperatures can impair gonad steroid synthesis, reduce egg fertility, and embryo survival in species like Atlantic salmon [38,39]. Optimal temperature ranges vary among species, and temperatures outside these ranges can reduce reproductive performance [40]. Temperature also influences maturation rates, which can have positive or negative outcomes for aquaculture, depending on the context [41,42].

3.1.3 Nutritional and Digestive Metabolism

Temperature affects nutrition, feeding practices, and behaviours in aquatic animals, with direct impacts on basal metabolism and energy needs [43,44]. Rising temperature increases standard metabolic rate, maintenance energy requirements, and feed conversion ratios (FCR), reducing feed efficiency. Optimal temperature ranges vary among species, with decreased feed efficiency occurring at either end of the range [45,46]. Temperature-driven changes in FCR may also affect nutrient digestibility, although research suggests minimal impacts on protein and lipid digestibility in salmonids [47,48, 49,50].

3.2 Sea Level Rise

Sea level rise (SLR) is expected to significantly impact aquaculture production, particularly in coastal areas, through increased flooding, saltwater intrusion, and damage to infrastructure [51,52]. The Intergovernmental Panel on Climate Change (IPCC) projects a 0.1-1.0 m SLR by 2100, with continued rise beyond 2100 [53]. This will lead to loss of culture areas, increased salt intrusion into coastal groundwater, and changes in species composition and ecosystem productivity [54,55]. Furthermore, SLR will alter the hydrology and hydrography of water systems, affecting the distribution and abundance of nutrients, and potentially leading to increased eutrophication and harmful algal blooms.

The impacts of SLR on aquaculture will vary by region, with some areas experiencing more frequent and severe flooding, while others may face increased drought and water scarcity. In some cases, SLR may create new opportunities for brackish water culture of high-value species, such as shrimp and mud crab [56,51]. However, these opportunities will need to be carefully managed to avoid exacerbating existing environmental and social concerns.

Aquaculture practices, such as mangrove clearing, have historically exacerbated coastal flooding and erosion, but efforts to restore mangroves and promote sustainable aquaculture practices are underway [1,57]. The restoration of mangroves and other coastal ecosystems can help to mitigate the impacts of SLR on aquaculture, while also providing a range of ecosystem services, including shoreline protection, water filtration, and habitat for diverse marine species [58].

3.3 Ocean Acidification

Ocean acidification, caused by increased atmospheric CO_2 absorption by oceans, has profound implications for aquaculture. As atmospheric CO_2 levels rise, oceans absorb more CO_2, leading to reduced seawater pH, carbonate ion concentrations, and calcium carbonate minerals. This process, known as ocean acidification, impairs calcification, internal acid-base regulation, shell biomineralization, and energy metabolism in organisms with $CaCO_3$ shells [59, 60,61,62,63].

Ocean acidification has severe consequences for marine life, particularly for organisms with calcium carbonate shells. The reduced pH levels and decreased availability of carbonate ions hinder the ability of these organisms to build and maintain their shells. Shellfish, especially larvae, are vulnerable to ocean acidification, with reduced growth, development, and survival [64,65]. Finfish may also be affected, with impaired olfactory responses and receptor impairment [66,67]. Some macroalgal species may benefit from ocean acidification, while calcifying species may be negatively impacted [68,65].

The effects of ocean acidification on aquaculture can have significant economic implications. As the industry continues to grow, it is essential to understand the potential risks and consequences associated with ocean acidification. The impacts of ocean acidification on aquaculture are far-reaching. Economic losses have already been reported in some regions, particularly in shellfish aquaculture [64]. As marine-based aquaculture expands, climate change effects in marine systems will have a greater potential influence on global production.

3.4 Water Stress

Climate change is expected to exacerbate water stress issues in aquaculture, particularly in freshwater systems. The rapid expansion of freshwater aquaculture has led to major constraints on land use in key producing countries such as China, Indonesia, Bangladesh, Thailand, and India [69]. By 2050, numerous culture ponds are expected to be taken over by urbanization, leading to more widespread use of cages in small water bodies and greater production moving to open-water coastal areas [70]. Freshwater aquaculture production accounts for 64% of farmed food fish production globally [35].

Water scarcity is a significant concern for aquaculture, and climate change is expected to worsen this issue. Changes in precipitation patterns and increased evaporation due to rising temperatures will lead to reduced water availability, affecting aquaculture production. The predicted reduced water availability in major river systems in the deltaic regions of Asia, where major aquaculture activities exist, has to be considered in conjunction with saline water intrusion arising from sea level rise [71] and the expected changes in precipitation or monsoon patterns [6]. Sea-level rise and saline water intrusion are also expected to impact aquaculture in deltaic regions [3]. To mitigate these impacts, adaptive measures such as water conservation, recirculation technology, and integrated agriculture-aquaculture systems are necessary.

Implementing adaptive measures to address climate change impacts on aquaculture requires careful consideration of local conditions and resources. Effective solutions will depend on factors such as water availability, land use, and market demand. Recirculation technology can help conserve water, but its high capital and maintenance costs, as well as energy requirements, need to be addressed [72]. Offshore mariculture has been proposed as a means to increase food fish production with minimal environmental impacts, but technical, logistical, and financial challenges need to be overcome [73].

3.5 Salt Water Intrusion

Saltwater intrusion due to sea-level rise is a significant concern for coastal communities and aquaculture. As sea levels rise, saltwater is shifting landward, contaminating freshwater sources and affecting agriculture and aquaculture [74]. In low-lying coastal areas, such as the Mekong Delta, over 25 million people are at risk of drinking saline water [75]. A 30 cm sea-level rise is predicted in the Mekong Delta by 2050, accelerating saltwater intrusion [55].

Saltwater intrusion has already impacted aquaculture in some regions. In Bangladesh, salinization has affected crops, hindering freshwater prawn farming in rice paddies and contaminating drinking water [76]. In Vietnam, saltwater intrusion has threatened striped catfish farming [77]. Sea-level rise is expected to increase water levels during the rainy season and salt intrusion during the dry season, further threatening production [78]. However, saltwater intrusion may also present opportunities for some types of aquaculture. Areas unsuitable for agriculture could be repurposed for shrimp farming [79].

3.6 Extreme Weather and Climatic Events

Climate change is projected to increase precipitation-mediated flooding, affecting aquaculture production worldwide. This is particularly concerning for low-lying coastal areas, where flooding can cause significant damage to aquaculture facilities and infrastructure. Southeast Asia, peninsular India, eastern Africa, and the northern half of the Andes are expected to experience the largest increase in flood frequency [80]. Flooding can cause escapes, introduce predator species, and contaminate pond water, leading to significant economic losses [10,81]. Flooding is a major concern for aquaculture, as it can lead to significant economic losses and damage to infrastructure.

Extreme weather events, such as hurricanes and typhoons, are expected to increase in frequency and intensity, damaging coastal aquaculture operations. El Nino events may also drive increased interannual variability in regional temperature extremes [82]. Global warming is likely to lead to overall drying of land surfaces due to increased evaporation [83], although regions will vary.

Changes in precipitation patterns and increased evaporation due to rising temperatures will lead to reduced water availability, affecting aquaculture production. Increased storminess has been identified as having potentially catastrophic impacts for global fisheries and coastal aquaculture [84].

Severe climatic events, such as cyclones, waves, and storms are expected to influence aquaculture development especially marine ornamental products, and those in coastal areas [85]. For instance, coral and giant clam farmers in tropical villages may face increased losses due to bleaching, while those in sub-tropical regions may suffer greater risks, such as loss of production equipment and stock due to rougher sea conditions related to stronger cyclones. The occurrence of storm surges, waves, and coastal erosion are considered the most dangerous threats to aquaculture production and other related coastal activities [11]. However, storms may also promote environmental sustainability by mixing water columns and nutrients [14].

3.7 Health

Climate change poses significant challenges to aquaculture health management and disease control globally [86,87,88]. Large-scale disease outbreaks have become an increasing economic concern as global aquaculture production expands [89,90]. The aquaculture industry is vulnerable to climate-related impacts, which can lead to significant economic losses and compromise food security. Research on climate change effects on marine and freshwater diseases is limited [91,92], and long-term datasets are scarce [91,93]. This knowledge gap hinders our ability to predict and prepare for the impacts of climate change on aquaculture health.

Climate change will significantly impact parasitism and disease in freshwater and marine ecosystems, where most aquaculture occurs [94,95]. The emergence, translocation, and virulence of diseases, parasites, and pathogens are potentially damaging effects of climate change [93]. Changes in temperature and precipitation patterns can facilitate the spread of diseases and parasites, compromising aquaculture health. Rapid environmental fluctuations and extreme events, such as anomalous thermal events, may reduce the capacity for recovery between events [96,97,98]. Climate change will affect disease through enhanced parasite/pathogen metabolic rates, changes to host distribution and behaviour, and compromised host immune function [95, 93,99]. Understanding these impacts is crucial for developing effective strategies to mitigate the effects of climate change on aquaculture health.

Predicting specific outcomes is challenging due to varying responses to temperature, cumulative and synergistic effects with other anthropogenic stressors, and adaptive capacity of hosts, pathogens, and parasites [100,101]. Parental exposure to an environmental stressor may also influence offspring resistance, depending on the duration of exposure [102]. The complexity of these interactions highlights the need for continued research and monitoring to better understand the impacts of climate change on aquaculture health. The various effects of climate change on aquatic systems (e.g. changes to temperature, precipitation, salinity, acidification, oceanic circulation, water levels and flow, eutrophication, stratification, ice cover, ultraviolet radiation) all have the potential to affect host–parasite interactions [94,95] and aquatic animal health.

3.7.1 Water Temperature and Infection

The relationship between water temperature and infection is complex, with some studies suggesting that warming waters may facilitate infection and mortality in aquaculture. Aquaculture diseases at lower latitudes progress more rapidly and have higher cumulative mortality, with tropical countries suffering proportionally greater losses during disease outbreaks, having less time to mitigate losses [103]. Temperature variability, rather than simple increases in temperature, may have a greater impact on disease dynamics [104,105]. This complexity highlights the need for further research into the impacts of temperature on aquaculture health.

For example, epizootics of marine trematodes in coastal host populations are predicted to be more common during years with high North Atlantic Oscillation index values [106]. This suggests that large-scale climate patterns can influence the dynamics of disease outbreaks in aquaculture. Not all infectious organisms are expected to thrive under warming waters [107,91]. A 21-year dataset on bacterial and protozoan pathogens in fish farms from northern Finland showed that while the prevalence of some pathogens increased with mean water temperature, others decreased or showed no change [91].

The temperature ranges of pathogens can be narrow, and rapid temperature changes can reduce the time available for infection [12]. Pathogens associated with cooler water may have lesser potential for spread under warming conditions [107,12]. However, there is no assurance that pathogen temperature ranges or virulence will remain static under environmental change. Warming temperatures within optimal ranges can increase the growth rates of aquaculture species, potentially favouring the evolution of increased pathogen virulence [108].

3.7.2 Water Quality

Water quality parameters, including pH, salinity, dissolved oxygen, and eutrophication, can become health stressors in aquaculture. Ocean acidification may negatively impact marine aquaculture, affecting structural formation, tissue damage, reproduction, and growth. Changes in water quality can have significant impacts on the health of aquatic organisms. For example, changes in pH and oxygen levels can increase the susceptibility of organisms to disease.

Ocean acidification can increase the abundance of pathogens, such as Vibrio spp., and impair immune functions in marine species [109,110]. This can lead to increased disease outbreaks and reduced growth rates in aquaculture species.

Changes in salinity can also impact disease outbreaks, with some studies showing that reduced salinity can control infections, while increased salinity can decrease infection rates. Reduced salinity has been shown to control Dermo disease in oysters and sea lice on salmon [98,111]. Saltwater intrusion and storm surge-based flooding can increase disease susceptibility in coastal freshwater species. Saltwater intrusion into freshwater prawn culture areas in Bangladesh has been linked to several viral and bacterial infections [76].

3.7.3 Immune Functionality

Climate change can lead to immuno-suppression in aquatic organisms, making them more susceptible to disease [112]. Temperature plays a crucial role in immune functionality, with optimal temperatures varying between species [99]. The immune response of fish is affected by temperature, with both innate and acquired immune responses influenced by changes in temperature [113,114]. Innate parameters are active at lower temperature ranges, while acquired immune parameters are more effective at higher temperatures [115].

Temperature extremes can impair immune function and contribute to disease outbreaks [116]. This is particularly concerning in the context of climate change, where increased frequency and severity of extreme weather events are expected. Changes in water quality parameters, such as ocean acidification and dissolved oxygen, can also impact immune functionality [117]. These changes can have significant impacts on the health and resilience of aquatic organisms. While temperature is expected to decrease generation time of many bacterial, viral, and fungal diseases, the acquired immune system of finfish is expected to operate more effectively at warming temperatures (assuming the fish are operating within their thermal limits) and, therefore, with greater potential to overcome infection [12].

3.7.4 Diseases and Harmful Algal Blooms

Climate change is expected to increase the occurrence of diseases in aquaculture production systems, leading to reduced profits and affecting the social and economic sustainability of aquaculture. Warmer conditions may result in the establishment of exotic diseases, and the vulnerability of finfish and shellfish to pathogens is a major determinant of diseases [18,99]. Rising temperature is likely to accelerate the replication rate, virulence, life cycle longevity, and transmission of pathogens among several finfish and shellfish species [95]. This can lead to increased disease outbreaks and reduced growth rates in aquaculture species. Moreover, the increasing temperature pressures may promote the emergence of epizootic diseases in aquaculture and cause serious economic challenges.

Changes in climatic conditions are also associated with the outbreak of harmful algal blooms, which can have negative implications on the social and economic aspects of aquaculture sustainability [118,119,120,79,121,122]. Harmful algal blooms can cause stress or kills in finfish and shellfish, and some studies have reported pathologies in several organs of bivalve mollusks resulting from these blooms [123,124]. The impacts of climate change on aquaculture health are complex and multifaceted.

3.8 Genetics and Changing Climate

Aquatic organisms exhibit varying degrees of genetic and epigenetic responses to climate stressors, both between and within populations, and across different life stages. This variability suggests that some individuals may be more resilient to climate stressors than others. Environmental exposure can induce plastic responses in early larval stages, and parental exposure can confer traits to offspring. Selective breeding may offer a potential avenue for adapting species to climate change stressors. However, the genetic correlations between climate-related traits and currently selected traits, such as disease resistance, are poorly understood. Moreover, the rate and capacity of aquaculture populations to adapt to climate change stressors over long-term exposures and multiple generations remain largely unquantified.

3.8.1 Acclimation

Phenotypic plasticity allows individuals within a population to respond differently to climate stressors, enabling them to adapt and function in new environments [125]. This capacity for acclimation can be influenced by the strength and rapidity of environmental changes. The ability of individuals to adapt to changing environments is crucial for their survival. Environmental changes can trigger various physiological and morphological responses, allowing individuals to cope with the new conditions.

Temperature changes can also trigger specific gene expressions, such as heat tolerance in Arctic charr [126] and immune-related genes in Atlantic cod [127]. This suggests that some individuals may be more resilient to climate stressors than others. However, extensive plasticity in finfish is not universal and can be limited by factors such as genetic diversity and stressor levels. A lack of plasticity can constrain the ability of populations to adapt to changing environments, leading to reduced fitness and increased vulnerability to extinction. Plasticity may increase the time available for adaptation, it can also weaken selective pressure and slow the pace of adaptation [128]. Ultimately, plasticity has significant implications for how entire ecosystems respond to climate change stressors [129].

3.8.2 Adaptation Potential

Transgenerational acclimation, where parental exposure to environmental stressors influences offspring adaptation potential, has been reported in various aquaculture species. Studies have shown that parental exposure to ocean acidification can enhance offspring tolerance in some species, such as the green sea urchin [130] and the Sydney rock oyster [131]. However, transgenerational acclimation is not universally assured and may depend on trait heritability and selection pressure [132]. Changes in species' range expansions due to climate change may also lead to hybridization and introgression, affecting phenotypic variation in offspring and potentially impacting production traits and fitness [133].

3.8.3 Selection

Selective breeding in aquaculture can lead to significant genetic changes in aquatic species, such as salmonids and oysters, over relatively few generations [134,135,136,137,138]. This can result in improved production traits, such as growth rate and disease resistance. However, this artificial selection pressure can also reduce genetic diversity, overall population fitness, and resilience to future environmental change [139]. This highlights the need for careful consideration of the potential impacts of selective breeding on the long-term sustainability of aquaculture species.

Epigenetics plays a crucial role in understanding the interaction between phenotype and environment, where phenotypic changes may be heritable without changes to the genetic sequence itself [140,141]. Epigenetic mechanisms can allow organisms to adapt to changing environmental conditions, such as temperature and water quality. Breeding programs in aquaculture aim to improve production traits, but may inadvertently reduce variability and stock adaptive capacity, disregarding specific traits important to future climate change scenarios [142].

IV. Indirect Impacts of Climate Change on Aquaculture

Climate change will have indirect impacts on aquaculture through changes in fisheries, which provide inputs such as feed and seed. These impacts will affect the suitability of areas for aquaculture species, the availability and prices of resources like fish protein for fish feed, and the production of aquafeed. The availability and prices of fishmeal and fish oil, key ingredients in aquafeed, will be affected by climate-driven changes in fisheries [56]. Additionally, the increasing diversion of plant materials for biofuel production may lead to limited availability and high costs of aquafeed ingredients.

4.1 Fishmeal and Fish Oil Supplies

The aquaculture sector's reliance on fishmeal and fish oil, primarily derived from small pelagic fish, is a significant indirect impact of climate change. In 2003, aquaculture consumed 2.94 million tonnes of fishmeal, equivalent to 14.95-18.69 million tonnes of forage fish [143].

Climate change is predicted to decrease the biological productivity of the North Atlantic by 50% and ocean productivity worldwide by 20% [4]. This will impact the availability of raw materials for fishmeal and fish oil production, leading to price fluctuations and reduced supplies.

To mitigate these impacts, there is a need to shift towards omnivorous and filter-feeding finfish aquaculture in tropical and subtropical regions [144,145]. This would require changes in consumer and market demands, as well as a shift in public opinion towards more sustainable aquaculture practices.

4.2 Other Feed Ingredients Used in Aquaculture

The aquaculture industry is facing new challenges due to the increasing demand for biofuels, which is driving up the prices of feed ingredients such as soybean meal and corn meal [145]. This trend is likely to continue, making it essential for the aquaculture industry to find alternative feed sources. The rising demand for biofuels is not the only challenge facing the aquaculture industry. Rising food prices and diminishing returns for farmers [146], also termed a “silent tsunami” [147] are also putting pressure on the industry to secure affordable feed ingredients. This is particularly concerning, as profit margins in aquaculture are already extremely narrow. The use of agricultural by-products in aquafeeds, such as soybean meal and oilcakes, can help mitigate these impacts [148]. These by-products are often cheaper and more sustainable than traditional feed ingredients, making them an attractive option for aquaculture producers. However, climate change is expected to negatively impact tropical terrestrial agriculture, which is a major source of these by-products [149]. This could lead to reduced availability and increased prices for these by-products, further exacerbating the challenges facing the aquaculture industry.

4.3 Trash Fish/Low Valued Fish/Forage Fish Supplies

The aquaculture sector in Asia-Pacific region relies heavily on trash fish or low-valued fish as a direct feed source, with estimated usage ranging from 1.6 to 2.8 million tonnes per year [150]. This practice is not only unsustainable but also vulnerable to climate change impacts. The use of trash fish or low-valued fish in aquaculture is a significant concern, as it can lead to overfishing and depletion of wild fish populations. Furthermore, the reliance on these fish sources can also impact the livelihoods of small-scale fishers who depend on these fisheries. The Indian Ocean, which is warming rapidly, is expected to experience major changes in productivity and current patterns, further exacerbating the situation [5]. Extreme climatic events, such as changes in monsoonal rain patterns, will also impact inshore fish productivity and supplies of trash fish or low-valued fish [6]. These changes will have significant impacts on the aquaculture sector, particularly in tropical Asia, where many countries rely heavily on aquaculture for food security and livelihoods. The impacts of climate change on the aquaculture sector in tropical Asia are likely to be significant, particularly for small-scale fishers who rely heavily on specific fisheries [3].

4.4 Impacts on Biodiversity

Climate change is expected to have significant impacts on biodiversity, with predictions suggesting that up to one in five species could be extinct by the current levels of greenhouse gas emissions [151]. The aquaculture sector's reliance on alien species and translocations of seed stocks between nations and watersheds could exacerbate these impacts [152,150]. The introduction of alien species for aquaculture purposes can lead to competition with indigenous species for food and space, alteration of habitats, and transmission of pathogenic organisms [153,154]. Climate change could further exacerbate these impacts, particularly in temperate regions where disease transmission among filter-feeding molluscs and fish could increase. The culture of alien species such as salmonids, tilapias, and white legged shrimp could be impacted by climate change, with warming temperatures potentially extending the distribution range of tilapias and shrimp, but narrowing it for salmonids.

Coral bleaching and associated loss of biodiversity have been relatively well-documented, with an estimated 60% decline in coral reefs by 2030 [71]. However, the decline of coral reefs could be mitigated by the increasing production of aquaculture, particularly for species such as grouper, which could reduce the demand for wild-caught fish and alleviate pressure on coral reefs. Extreme weather events could lead to mass escapes of aquaculture stocks, potentially impacting local biodiversity and genetic makeup of wild stocks [155,156]. Therefore, measures to prevent and mitigate escapes should be implemented, particularly in areas vulnerable to extreme weather events.

V. Potential Impacts of Aquaculture on Climate Change

The aquaculture sector has experienced rapid growth over the last two decades, making it the fastest growing primary production industry [1]. However, the sector has faced criticism for its environmental impacts, including the use of fishmeal and fish oil, and mangrove clearing for shrimp farming [144,145,157,158,159]. Despite these criticisms, aquaculture also makes positive contributions to the environment, including helping to mitigate climate change. However, these benefits are often overlooked in favour of criticisms of the sector's environmental impacts. In reality, all food production systems have environmental costs, and these costs should be compared fairly across different sectors [160]. By recognizing the positive contributions of aquaculture, it is possible to develop a more nuanced understanding of the sector's role in addressing global environmental challenges like climate change.

Aquaculture, like all forms of farming, incurs energy costs, but the sector offers a diverse range of over 300 species to choose from, many of which have lower environmental costs [1]. Market demand drives the production of high-valued species such as shrimp, salmonid, and marine finfish, which have higher environmental costs due to energy-intensive practices like aeration and water exchange. Shrimp aquaculture, in particular, has high environmental costs due to its energy-intensive nature and processing requirements. However, studies have shown that the culture of native species like the tiger shrimp (P. monodon) is more ecologically cost-effective than the alien species P. vannamei [161,162].

In contrast, the majority of aquaculture production is focused on more environmentally friendly commodities like molluscs and seaweed, which contribute to carbon sequestration. Seaweed culture, in particular, has a high potential for carbon sequestration due to its rapid turnover and high yields. Criticism of the aquaculture sector for its environmental impacts is often unfair, as it is based on a small proportion of production that accounts for less than 10% of global aquaculture production.

VI. Mitigation and Adaptation

Climate change poses significant risks to aquaculture, including impacts on health, food security, livelihoods, water supply, human security, and economic development [53]. The aquaculture industry must adopt new strategies and technologies to mitigate and adapt to these changes. The rate of future climate change is predicted to be more rapid than previous natural changes, and the resilience of species and systems is being compromised by concurrent pressures such as fishing, loss of genetic diversity, habitat destruction, pollution, introduced and invasive species, and pathogens [163]. Therefore, mitigation and adaptation efforts are crucial to reduce the impacts of climate change on aquaculture.

Mitigation efforts focus on reducing greenhouse gas (GHG) emissions, primarily CO_2, which accounts for over 60% of human-enhanced increases. This can be achieved through electrification, hydrogen, sustainable bio-based feedstocks, product substitution, and carbon capture utilization and storage [53]. In aquaculture, mitigation efforts can include the use of environmentally friendly practices and technology, such as solar energy, proper feeding practices, and sustainable wastewater management to minimize air and water pollution. Feed production in aquaculture is particularly seen as the sector's major contributor to GHG emissions [164].

Adaptation strategies, on the other hand, focus on building resilience to the consequences of climate change. This includes diversification of livelihoods, shifting to climate-resilient species, and improving governance and management systems [165]. Diversification of livelihoods may be one of the keys to successful adaptation, as it gives producers options from which they can derive their livelihoods and build resilience to climate change impacts [166]. This can involve combining aquaculture production systems with other sectors, such as agricultural systems. Incorporating indigenous knowledge into adaptation strategies can also be effective, as it provides specific details about the physical environment, infrastructure systems, livelihood status, behaviour, governance organization, and other attributes that are crucial for managing community resources [167]. Building adaptive capacity through insurance schemes, particularly for small-scale producers, can also help to build resilience to climate change impacts [168]. However, the viability of the aquaculture insurance business may depend on how efficient and lower-risk aquaculture becomes, apart from climate change risks [169].

6.1 Adaptation Strategies

6.1.1 Diet and Nutrition

Diet and nutrition play a crucial role in helping aquatic organisms adapt to climate change stressors. For climate change stressors, this has been documented for several mollusc species in response to ocean acidification exposure, where energy intake and assimilation may be unaffected in conditions of plentiful food [170,171]. The nutritional requirements of aquatic organisms can be affected by climate change, and nutritional bioenergetic models have been developed to estimate optimal digestible protein and energy requirements under different temperatures [172, 173,174]. These models can help inform feeding strategies that support the health and resilience of aquatic organisms in the face of climate change. Dietary flexibility of herbivorous and omnivorous species enables the use of alternative ingredients, reducing reliance on fish-derived feed ingredients [175,176]. However, sourcing aquaculture feed ingredients from terrestrial crops may shift environmental impacts to those associated with increased crop demand [177]. This highlights the need for sustainable and environmentally-friendly feed sourcing strategies that balance the nutritional needs of aquatic organisms with the environmental impacts of feed production.

6.1.2 Genetics and Biotechnology

Aquatic organisms have the potential to adapt to climate change through genetic and biotechnological approaches [140,178]. The epigenetic response potential of fishes and marine invertebrates suggests some level of adaptive capacity to climate change. Selective breeding programs for desirable traits are already common in aquaculture, and this may provide additional options for climate change adaptation. Some species, such as carps and prawns, have shown productivity gains ranging from 7 to 12% per generation through conventional selective breeding approaches [179]. Breeding programs can also focus on specific climate change performance traits, such as increased calcification rates in oysters [180]. This approach can help improve the resilience of aquatic organisms to climate change stressors, such as ocean acidification. Genomic approaches and gene banking can also be used to improve traits and preserve genetic variability [181,182]. This can provide a biological insurance for future needs of aquaculture breeding and stock selection, and can help maintain genetic diversity in the face of climate change.

6.1.3 Management and Engineering Solutions

The global aquaculture sector has demonstrated adaptability and ingenuity, which will be crucial for climate change adaptation. Adaptation strategies will likely focus on management and husbandry practices, which will be complemented by engineering solutions [183,10]. These approaches will enable the aquaculture sector to creatively address climate-related challenges and ensure the long-term sustainability.

6.1.3.1 Aquaculture Diversification

Diversification of farmed species and technologies is a growing trend in aquaculture globally [184]. This rapid diversification and domestication of new species for aquaculture, especially in mariculture, highlights the industry's adaptability and potential for growth [185]. Aquaculture practices such as polyculture and Integrated

Multi-Trophic Aquaculture (IMTA) can enable continued production if one crop fails and are advocated for climate change adaptation [186,187,188]. Co-culture can also reduce competition for resources and improve water quality [189,190]. Additionally, culture-based fisheries and air-breathing species are being explored as viable options for climate change adaptation [191,36].

6.1.3.2 Relocation

Choosing farm locations that are less impacted by climate change effects is a key adaptation strategy in aquaculture [192]. This approach can help reduce exposure to climate-related risks such as sea-level rise, drought, thermal stress, and flooding [193,194,195,196,197]. The use of GIS or remote sensing tools can aid in selecting optimal locations for aquaculture [198,199,200,201,195,202,203,204,205]. Relocating to areas with optimal water quality can also help reduce disease risks by limiting pathogen or parasite exchange between wild and cultivated species [206,90]. However, optimal water quality conditions may not be suitable for all life stages of a species, highlighting the need for separate site locations for broodstock and grow-out [207]. Deeper ponds can provide a thermal refuge and greater dissolved oxygen reserves, making them less sensitive to environmental factors during dry seasons [208]. Overall, careful consideration of farm location and design can help mitigate the impacts of climate change on aquaculture.

6.1.3.3 Flooding and Storm Protection

Protection against floods will be a combination of management strategies and age-old engineering approaches, such as increasing physical barriers or use of tanks and inland enclosures [81,187]. The scope of response will be a function of damage potential. An increase in sea level of 0.1 m requires coastal infrastructure such as wharfs to be raised by >0.1 m (an allowance) in order for the same historical flood frequency to be maintained [209]. Effective flood protection measures can reduce the risk of crop loss and damage to infrastructure. In areas with predictable seasonal flooding, routine flood-response management strategies are already in place, such as harvesting fish prior to flood periods or dropping pond water levels [210,211] and excess water volume is pumped out of ponds in some Indian regions [10]. These strategies can help minimize losses and ensure business continuity.

Natural barriers, such as mangroves, reefs, and coastal vegetation, can also provide protection against storm surges [212,213,58]. Restoring coastal mangroves and promoting integrated mangrove-shrimp farming can help reduce mangrove loss and increase carbon sequestration [214,215,216]. Seaweed aquaculture has also been suggested as a strategy to dampen incoming wave energy and protect shorelines [185]. These ecosystem-based approaches can provide long-term benefits for both aquaculture and the environment. In some cases, flooding can expand aquaculture opportunities, such as floodplain ponds or Whedo aquaculture systems [217,218]. However, climate change also introduces new challenges, such as increased escapes and disease risks, emphasizing the need for good biosecurity and infrastructure design [219,220,221]. Aquaculture operations must adapt to these changing conditions to remain resilient and sustainable.

6.1.3.4 Localized Mitigation

Direct mitigation of the localized environment is possible in some circumstances, particularly in pond culture, which is the most common method of global aquaculture production. Ponds can be managed to control environmental variables such as water quality, temperature, and oxygen levels through techniques like aeration, water treatment, and shading [165,188,10]. For example, oxygen tablets and aeration can increase dissolved oxygen levels, while pumping in freshwater can supplement water during dry seasons. Sediment buffering using crushed shell has been tested to increase sediment alkalinity, pH, and aragonite saturation states, thereby reducing shell dissolution and promoting larval recruitment in infaunal marine species [222]. Seaweed or macrophyte culture has also been suggested as a method to provide localized mitigation, act as a net producer of oxygen, sequester carbon dioxide, and increase pH [79,223,224,185,225]. Land-based or closed containment rearing strategies can also be used to protect sensitive life stages from environmental stressors or control rearing conditions to enable adaptive responses. These strategies enable water quality control through recirculation approaches, strategic water intake, or bio-buffering [226,227].

6.1.4 Improving Information

Timely information is crucial for aquaculture management, enabling real-time monitoring, early warning systems, and long-term predictions. Initiatives to promote local-level adaptation through training, data collection, analysis, and sharing, are advocated as an approach to connect environmental data with broader forecasts to support decision making by local aquaculture stakeholders [192,187]. Real-time monitoring can alert farmers to deleterious conditions, such as low oxygen levels or high temperatures, allowing for prompt action. Advances in technology and networking enable online tracking of water quality parameters. Microsensor technology monitors shellfish heart rates, assessing environmental stressors [228]. Early warning of acute, deleterious events can improve response times of farmers [229]. Early warning systems have been strongly advocated in order to reduce aquatic food safety risk posed by climate change-related natural disasters, such as contamination (e.g. pathogens) from extreme weather events [230,219]. Long-term climate predictions can inform strategic planning and decision-making for aquaculture operations. Among the most pressing predictive needs in aquaculture is the ability to forecast disease outbreaks. Early detection followed by quick targeted responses can reduce the impact of disease [206,111]. The use of GIS-based statistical models that enable spatially distributed determinants of aquatic health and disease for risk mapping have been encouraged [231]. Aquaculture zoning and monitoring are also essential adaptation measures. Effective integrated monitoring systems can provide early detection of diseases, pest species, and environmental changes, enabling prompt action to mitigate impacts. Implementing risk communication strategies and early warning systems can also help prepare stakeholders for potential risks.

6.1.5 Governance

Climate change poses significant challenges to aquaculture, requiring adaptive and resilient strategies to maintain sustainability. National comprehensive climate change adaptation strategies often overlook aquaculture, emphasizing the need for sector-specific adaptation and mitigation strategies. Effective governance, ecosystem resilience, and human adaptive capacity are crucial determinants of vulnerability [232]. Regulatory frameworks must be reformed to facilitate adaptation, innovation, and expansion in aquaculture, while maintaining environmental regulation [233,234].

6.1.5.1 Policies

The United Nations Framework Convention on Climate Change (UNFCCC) has established various initiatives to support climate change adaptation and mitigation in developing countries. The National Adaptation Programmes of Action (NAPAs) and National Adaptation Plans (NAPs) provide frameworks for countries to prioritize and implement adaptation measures, including those related to aquaculture [235,236]. Additionally, the Paris Agreement's Nationally Determined Contributions (NDCs) encourage countries to develop and communicate their climate change mitigation and adaptation strategies, with several countries highlighting aquaculture as a key sector for adaptation and mitigation [192].

VII. Conclusion

Climate change poses significant threats to the sustainability and productivity of aquaculture worldwide. Rising temperatures, ocean acidification, sea-level rise, and changes in precipitation patterns are altering the delicate balance of aquatic ecosystems, affecting the growth, survival, and productivity of farmed species. The impacts of climate change on aquaculture are far-reaching, with consequences for food security, livelihoods, and the environment. To mitigate these impacts, it is essential to develop and implement effective adaptation and mitigation strategies, including improvements in diet and nutrition, genetics and biotechnology, management and engineering solutions, and governance and policy frameworks. Furthermore, enhancing information sharing, improving climate forecasting, and promoting sustainable aquaculture practices are critical for building resilience and promoting the long-term sustainability of the aquaculture industry.

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