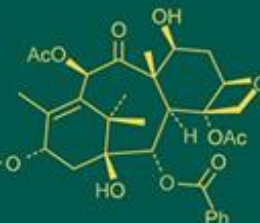
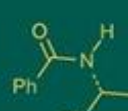
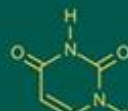
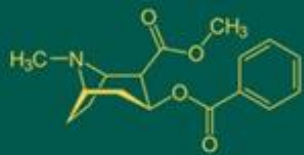


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Climate change impacts on aquatic ecosystems and fisheries resources: Drivers, consequences, adaptation strategies, and policy responses

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Abstract

Climate change has emerged as one of the most significant global threats to aquatic ecosystems and fisheries resources, profoundly altering environmental conditions, biodiversity, and the sustainability of aquatic food systems. Rising water temperatures, ocean acidification, deoxygenation, sea-level rise, and the increasing frequency of extreme climatic events are reshaping freshwater, estuarine, and marine ecosystems through complex and interacting pathways. These stressors influence fish physiology, species distribution, reproductive success, habitat integrity, and trophic interactions, while simultaneously increasing the prevalence of harmful algal blooms, invasive species, and infectious diseases. Consequently, capture fisheries and aquaculture are experiencing declining productivity, increased production risks, and growing socio-economic challenges, particularly in developing countries where fisheries contribute substantially to food security, nutrition, and livelihoods. This review synthesizes current scientific knowledge on the major climate-driven stressors affecting aquatic ecosystems and critically examines their ecological, biological, and socio-economic consequences for fisheries and aquaculture. Furthermore, it highlights climate adaptation and sustainable management strategies, including climate-smart fisheries and aquaculture, ecosystem-based fisheries management, habitat conservation and restoration, recirculating aquaculture systems, biofloc technology, integrated multi-trophic aquaculture, early warning systems, selective breeding, and community-based governance. The review also discusses international and national policy frameworks supporting climate resilience, such as the Paris Agreement, Sustainable Development Goals, FAO's Blue Transformation initiative, and India's Pradhan Mantri Matsya Sampada Yojana. Finally, key research gaps are identified, including the need for long-term environmental monitoring, improved understanding of tropical fisheries, climate-informed disease prediction, advanced genomic approaches, and integrated ecological-economic assessments. Strengthening climate-resilient management through science-based policies, technological innovation, and ecosystem conservation will be essential for safeguarding aquatic biodiversity, ensuring sustainable fisheries production, and enhancing global food security under future climate scenarios.

Keywords: Climate change, aquatic ecosystems, fisheries, aquaculture, climate-smart fisheries, ocean acidification, deoxygenation, sustainable aquaculture, climate resilience

1. Introduction

Aquatic ecosystems, including rivers, lakes, wetlands, estuaries, and oceans, harbor an extraordinary proportion of global biodiversity and provide essential ecosystem services that sustain food security, nutrition, and livelihoods for billions of people. Fish and other aquatic foods supply at least 20% of the animal protein intake for more than three billion people worldwide, while fisheries and aquaculture support the livelihoods of over 600 million people globally (FAO, 2024; Costello *et al.*, 2020) ^[1, 2]. In 2024, aquaculture production of aquatic animals surpassed capture fisheries production for the first time, highlighting the increasing importance of sustainable aquaculture in meeting global food demand (FAO, 2024). Climate change has emerged as one of the greatest threats to aquatic ecosystems and fisheries. Rising atmospheric concentrations of greenhouse gases have increased global temperatures, altered precipitation patterns, intensified hydrological extremes, accelerated sea-level rise, and increased the frequency of marine heatwaves (IPCC, 2023; Cooley *et al.*, 2022) ^[3, 4]. Since most aquatic organisms are ectothermic, their metabolism, growth, reproduction, immune competence, and survival are closely linked to environmental conditions such as temperature, dissolved oxygen, salinity, and pH (Pörtner, 2010; Cooley *et al.*, 2022) ^[5].

The IPCC Sixth Assessment Report identifies ocean warming, acidification, deoxygenation, altered freshwater flow regimes, sea-level rise, and extreme climatic events as the principal climate-driven stressors affecting aquatic ecosystems. These stressors frequently interact synergistically, reducing ecosystem resilience and increasing vulnerability beyond the effects of any individual stressor (Cooley *et al.*, 2022; IPCC, 2023)^[4]. Recent studies further indicate that marine heatwaves have become more frequent and intense over the past century, causing large-scale mortality of marine organisms, biodiversity loss, and disruption of ecosystem functioning (Smale *et al.*, 2019; Oliver *et al.*, 2021)^[6, 7]. Climate-induced environmental changes are already producing measurable ecological and economic consequences. Many marine and freshwater species are shifting their geographical distributions toward higher latitudes and deeper waters in response to warming, resulting in significant changes in fisheries productivity, species composition, and ecosystem dynamics (Free *et al.*, 2019)^[8]. Coral reefs, mangroves, seagrass meadows, wetlands, and other critical nursery habitats are increasingly threatened by rising temperatures, ocean acidification, coastal erosion, and sea-level rise, jeopardizing biodiversity conservation and fisheries sustainability (Hoegh-Guldberg *et al.*, 2019; IPBES, 2019)^[9]. Although aquaculture offers greater management control than capture fisheries, it remains highly vulnerable to increasing water temperatures, deteriorating water quality, emerging diseases, harmful algal blooms, and extreme climatic events (Barange *et al.*, 2018; Froehlich *et al.*, 2024)^[10]. These climate-related challenges threaten production efficiency, fish health, and the sustainability of aquatic food systems. The socio-economic consequences of climate change are particularly severe for small-scale fishers and aquaculture farmers in developing countries, where fisheries contribute substantially to food security, employment, poverty alleviation, and rural development. Limited financial resources, inadequate infrastructure, and restricted access to adaptive technologies reduce their capacity to respond effectively to climate-related risks (Barange *et al.*, 2018; Golden *et al.*, 2021)^[10, 11]. Addressing these challenges requires a comprehensive transition toward climate-smart fisheries and aquaculture, ecosystem-based fisheries management, habitat conservation and restoration, selective breeding for climate resilience, technological innovations such as Recirculating Aquaculture Systems (RAS) and precision aquaculture, and coordinated national and international policy interventions (FAO, 2022; Froehlich *et al.*, 2024)^[12]. Accordingly, this review synthesizes current scientific evidence on the impacts of climate change on aquatic ecosystems and fisheries resources, critically examines adaptation and mitigation strategies, evaluates international and national policy initiatives ranging from the Paris Agreement to India's Pradhan Mantri Matsya Sampada Yojana (PMMSY), and identifies key research gaps and future priorities for developing resilient and sustainable aquatic food systems. This narrative review was developed by synthesizing published literature retrieved from major scientific databases, including PubMed, Scopus, Web of Science, and Google Scholar. Peer-reviewed research articles, review papers, book chapters, and reports published primarily in English (2005–2026) were identified using keywords related to climate change, aquatic ecosystems, fisheries, aquaculture, ocean acidification, deoxygenation, climate-smart fisheries, and ecosystem-based fisheries management. Additional references were obtained from FAO and IPCC publications and the reference lists of relevant studies. The selected literature was critically evaluated

and synthesized to summarize current knowledge, identify research gaps, and highlight future research priorities.

2. Climate change drivers affecting aquatic ecosystems

Anthropogenic climate change is now recognised as one of the foremost threats to aquatic ecosystems globally. Rising atmospheric concentrations of greenhouse gases principally carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) have driven sustained global warming, disrupted hydrological cycles, intensified the frequency and severity of extreme weather events, and accelerated sea-level rise as documented in the IPCC Sixth Assessment Report (Table 1) (Cooley *et al.*, 2022)^[4]. Collectively, these drivers are reshaping the physical, chemical, and biological structure of freshwater, estuarine, and marine systems, with consequences for biodiversity, fisheries productivity, and the ecosystem services these environments provide. Aquatic organisms are disproportionately sensitive to climatic change because even small shifts in temperature, dissolved oxygen, salinity, or pH can alter physiology, behaviour, reproduction, and survival. The IPCC AR6 WGII Chapter 3 assessment, led by Cooley and Schoeman, identifies ocean warming, marine heatwaves, and associated shifts in community composition as key drivers already producing measurable biodiversity loss and fisheries disruption. Because these stressors rarely act in isolation, their combined effect on ecosystem resilience is frequently greater than the sum of their individual impacts a synergism that complicates both prediction and management.

2.1 Rising water temperature

Water temperature is among the most influential variables governing aquatic ecosystem function, since nearly all aquatic organisms are ectotherms whose metabolic rates track ambient temperature directly. Sustained warming elevates metabolic demand and oxygen consumption while altering feeding behaviour and reproductive timing. Within a species' thermal tolerance range, moderate warming can transiently enhance growth; beyond that range, however, chronic thermal stress depresses growth, reproductive output, and overall fitness (Pörtner, 2010)^[5]. Mechanistically, Pörtner's Oxygen- and Capacity-Limited Thermal Tolerance (OCLTT) framework proposes that the mismatch between tissue oxygen demand and the organism's capacity to supply it is the primary factor restricting whole-animal tolerance to thermal extremes, with loss of aerobic scope marking the earliest stage of thermal stress as temperatures approach the edges of a species' thermal window. This principle helps explain why warming does not merely stress aquatic organisms but can fundamentally cap their body size and performance. Sustained warming is also redrawing the geography of aquatic life. Cheung *et al.* (2013)^[13] modelled the integrated response of more than 600 marine fish species to changes in distribution, abundance, and body size, projecting that assemblage-averaged maximum body weight could shrink by 14–24% globally between 2000 and 2050 under a high-emission scenario, with roughly half of that decline attributable to distributional and abundance shifts and the remainder to physiological constraints. Tropical and mid-latitude regions are projected to be disproportionately affected, with average reductions exceeding 20% findings with direct implications for regional fishery-dependent economies, since smaller average body size in exploited stocks translates into reduced potential catch. Warming water also holds less dissolved oxygen even as biological oxygen demand rises, a combination that frequently produces hypoxic conditions.

These conditions impair respiration and swimming performance, suppress immune function, and elevate mortality in fish populations, while simultaneously destabilising benthic communities and altering nutrient cycling. Elevated temperature further favours the proliferation of pathogenic bacteria, viruses, fungi, and parasites, weakening host immune defences even as pathogen transmission increases a combination linked to more frequent disease outbreaks in both wild fisheries and aquaculture, alongside coral bleaching, harmful algal blooms, and mass mortality events during marine heatwaves.

2.2 Ocean acidification

Ocean acidification is a direct chemical consequence of rising atmospheric CO₂. Oceanic uptake accounts for nearly one-third of anthropogenic carbon added to the atmosphere without which atmospheric CO₂ concentrations, and the warming they cause, would be considerably higher. This benefit is not without cost, however: as dissolved CO₂ reacts with seawater, pH and carbonate ion concentrations fall, reducing the level of calcium carbonate saturation that many marine organisms depend on to build and maintain their skeletons. Using thirteen ocean-

carbon-cycle models, Orr *et al.* (2005) [14] projected that under a business-as-usual emissions scenario, the Southern Ocean and parts of the subarctic Pacific would become undersaturated with respect to aragonite by 2100, decades sooner than earlier estimates had suggested. Building on this, Doney *et al.* (2009) [15] reviewed laboratory evidence showing that many calcifying species exhibit reduced calcification and growth rates under high -CO₂ conditions, a vulnerability that extends across corals, oysters, mussels, clams, echinoderms, and many planktonic taxa. Coral reefs are especially exposed, since reduced calcification compromises reef growth, structural complexity, and the habitat that reef structure provides to thousands of associated species. Acidification's effects are not confined to shell and skeleton-builders. Even in fish, which do not build calcium carbonate structures, physiological stress associated with acidified conditions can interfere with sensory perception, predator avoidance, reproductive behaviour, and larval development, altering energy allocation and reducing recruitment success. Taken together, ocean warming, acidification, and deoxygenation impose cumulative stress on marine organisms stress that compounds rather than simply adds, further eroding ecosystem resilience and fisheries productivity.

Table 1: Major Climate Change Drivers and Their Effects on Aquatic Ecosystems and Fisheries

Climate Change Driver	Environmental Changes	Biological Consequences	Fisheries and Aquaculture Impacts
Rising water temperature	Increased water temperature, reduced dissolved oxygen	Thermal stress, altered metabolism, reduced growth, impaired reproduction	Decline in fish productivity, increased mortality, species redistribution
Ocean acidification	Decreased pH and carbonate ion availability	Reduced calcification, impaired larval development, coral bleaching	Decline in shellfish production, habitat degradation
Deoxygenation	Reduced dissolved oxygen levels	Hypoxia, reduced swimming performance, immune suppression	Fish kills, lower production, increased disease susceptibility
Sea-level rise	Coastal inundation, saltwater intrusion	Loss of wetlands, mangroves and estuarine habitats	Reduced nursery grounds, lower fish recruitment
Extreme climatic events	Floods, droughts, cyclones and heatwaves	Habitat destruction, physiological stress, mass mortality	Infrastructure damage, production losses and livelihood disruption

3. Climate change impacts on aquatic ecosystems

Climate change is reshaping aquatic ecosystems through interacting physical, chemical, and biological pathways (Table 2). Rising water temperatures, ocean acidification, deoxygenation, shifting precipitation regimes, and more frequent extreme events are collectively eroding ecosystem resilience and biodiversity across freshwater, estuarine, coastal, and marine environments, with cascading consequences for fisheries productivity, food security, and livelihoods (Cooley *et al.*, 2022) [4].

3.1 Impacts on freshwater ecosystems

Freshwater systems rivers, lakes, reservoirs, wetlands, and streams are among the most climate-sensitive because their ecological processes are governed tightly by temperature, precipitation, and hydrological variability. Woolway *et al.* (2020) [16], in a global review of lake responses to climate change, documented that declining winter ice cover and rising lake surface temperatures are altering thermal stratification and mixing regimes; where these changes are not offset by increased precipitation or inflow, they also accelerate evaporation and drive declining lake levels and surface-water extent a particular concern in arid and semiarid regions. These hydrological shifts translate directly into biological stress. Prolonged droughts reduce stream connectivity and habitat availability, while extreme floods disrupt breeding grounds and alter sediment dynamics; reduced discharge concentrates contaminants and

nutrients, encouraging eutrophication and hypoxia. Cold-water fish, such as salmonids, face habitat contraction as temperatures exceed their thermal tolerance, while in tropical and subtropical regions, warming compounded by declining dissolved oxygen elevates physiological stress and disease susceptibility in both wild and cultured fish.

3.2 Impacts on marine ecosystems

Marine ecosystems are undergoing widespread transformation driven by ocean warming, acidification, deoxygenation, and marine heatwaves. Cheung *et al.* (2013) [13] found that these changes are already redistributing marine fish poleward and into deeper water, with implications for fisheries productivity and regional fishery economies as species move beyond their traditional harvesting grounds. Coral reefs are among the ecosystems most severely affected. Hoegh-Guldberg *et al.* (2017) [17] describe how elevated seasurface temperatures disrupt the coral-zooxanthellae symbiosis, triggering bleaching that reduces coral growth, reproductive capacity, and reef structural complexity with consequential declines in reef-associated biodiversity. Ocean acidification compounds this by impairing calcification, further limiting reef recovery. Mangrove forests and seagrass meadows face parallel threats from sea-level rise, coastal erosion, and storms. Alongi (2015) [18] notes that mangroves function as vital nursery habitats for commercially important fish and crustacean species while serving as disproportionately efficient carbon sinks; their loss

therefore compounds both biodiversity decline and reduced climate mitigation capacity. Seagrass ecosystems face similar pressure from warming, sedimentation, and storm disturbance, leading to habitat fragmentation.

3.3 Wetlands and estuarine ecosystems

Wetlands and estuaries are highly productive transition zones providing nutrient cycling, carbon storage, nursery habitat, and water purification service yet they are increasingly exposed to climate-driven hydrological change and sea-level rise. Shifting freshwater inflow and salinity gradients alter estuarine species composition and primary productivity, while saltwater intrusion into freshwater wetlands drives vegetation shifts and habitat degradation. Coastal wetlands face additional pressure from intensifying storm surge and shoreline erosion, undermining both their fisheries value and their coastal-protection function; estuarine fish and shellfish species dependent on stable salinity during early life stages are especially vulnerable to reduced recruitment success.

3.4 Biodiversity loss and species redistribution

Climate change is accelerating biodiversity loss through habitat degradation and physiological stress. [Pecl et al. \(2017\)](#) ^[19], in a global synthesis, showed that climate-driven species redistribution is already altering ecosystem functioning, human well-being, and the dynamics of the climate system itself, since range shifts create novel ecological interactions and disrupt existing food webs. Species with narrow thermal tolerances and limited dispersal capacity face the greatest risk of local extinction [Lawlor et al. \(2024\)](#) ^[20]. Building on this, [Cheung et al. \(2013\)](#) ^[13] demonstrated that the poleward and deeper-water shifts observed in marine fish are already reshaping fisheries catch composition and are projected to intensify through the twenty-first century, producing ecological mismatches between predators and prey and altering reproductive timing.

3.5 Alteration of food webs and primary productivity

Climate change is reshaping aquatic food webs by altering the abundance, distribution, and seasonal timing of primary producers and consumers. [Richardson \(2008\)](#) ^[21], reviewing zooplankton responses to warming, identified three consistent patterns: poleward range shifts, declining body size, and

critically shifts in phenological timing. Long-term Continuous Plankton Recorder data from the North Sea show that different plankton functional groups are advancing their seasonal peaks at markedly different rates (dinoflagellates by roughly three weeks, copepods by roughly ten days, over 45 years), a differential response that produces a mismatch between successive trophic levels and disrupts the synchrony historically underpinning fish recruitment. Ocean stratification associated with warming also reduces vertical nutrient mixing, constraining phytoplankton productivity in many regions, even as nutrient runoff from extreme rainfall drives eutrophication in freshwater and coastal zones together altering the food resources available to economically important fish species.

3.6 Harmful algal blooms (HABs)

Climate change is intensifying the frequency, duration, and geographic range of harmful algal blooms. [Gobler \(2020\)](#) ^[22] notes that coastal waters are simultaneously warming, acidifying, and deoxygenating, conditions that favour bloom-forming cyanobacteria and marine microalgae and are altering both the geographic distribution and toxin profiles of endemic bloom-forming organisms. HAB toxins cause fish kills and shellfish poisoning, while the oxygen depletion associated with bloom decomposition compounds fish mortality, together producing significant losses for fisheries, aquaculture, tourism, and public health

3.7 Invasive species

Climate change is also facilitating the spread of invasive aquatic species. [Rahel and Olden \(2008\)](#) ^[23] identify five principal pathways by which climate change alters the abiotic template of aquatic systems in ways that favour invaders: warming waters, reduced lake ice cover, altered streamflow, increasing salinity, and expanding water-development infrastructure such as canals and reservoirs each of which can open new invasion pathways or confer a competitive advantage on warm-adapted non-native species. These invasions frequently reduce native biodiversity, alter nutrient cycling, and compound the ecological challenges already imposed by other climate stressors, underscoring the need for integrated, ecosystem-based monitoring and management.

Table 2: Climate Change Impacts on Different Aquatic Ecosystems

Aquatic Ecosystem	Major Climate Stressors	Ecological Impacts	Consequences for Fisheries
Freshwater ecosystems	Warming, drought, altered rainfall	Reduced water availability, eutrophication, habitat fragmentation	Decline in freshwater fish production
Marine ecosystems	Ocean warming, acidification, marine heatwaves	Coral bleaching, species migration, deoxygenation	Changes in fish distribution and reduced catch potential
Wetlands	Sea-level rise, altered hydrology	Habitat degradation, biodiversity loss	Reduced spawning and nursery habitats
Estuarine ecosystems	Salinity fluctuations, sea-level rise	Altered species composition and productivity	Lower recruitment of commercially important fish and shellfish

4. Climate change impacts on fisheries resources

Climate change has emerged as one of the most serious threats to global fisheries resources, altering aquatic habitats, species distribution, productivity, and ecosystem functioning. Because fisheries depend directly on environmental conditions that regulate fish growth, reproduction, migration, and survival, climate-induced changes in water temperature, dissolved oxygen, ocean acidification, sea-level rise, and extreme events are affecting both capture fisheries and aquaculture worldwide. [Free et al. \(2019\)](#) ^[8] provide some of the clearest empirical

evidence of this: using temperature-specific production models across 124 fish populations spanning roughly one-third of reported global catch, they found that maximum sustainable yield declined by 4.1% globally between 1930 and 2010, with five ecoregions East Asia prominent among them experiencing losses of 15–35%. Overall, 8% of populations studied were significantly negatively affected by warming, compared with only 4% positively affected, indicating that losses are already outweighing gains at this relatively early stage of ocean warming. Beyond the biological signal, [Sumaila et al. \(2011\)](#)

[24] show that climate change is reshaping the economics of world fisheries as well as their biophysics by altering primary productivity, species distribution, and the potential yield of exploited stocks, warming directly affects fishing revenues, operating costs, and the incomes fishing communities depend on, independent of any change in fishing effort itself.

4.1 Capture fisheries

Capture fisheries are especially vulnerable to climate-induced environmental change because wild populations cannot be managed as intensively as cultured species. Rising sea surface temperatures have altered the spatial distribution, migration patterns, and abundance of many commercially important species. Cheung *et al.* (2013) [13] showed that marine fish are shifting toward higher latitudes and deeper water in response to warming, changes that are reshaping catch composition, reducing catch potential in tropical regions, and increasing fishing pressure in temperate and polar waters as species move across jurisdictional boundaries. This redistribution complicates fisheries governance, since many transboundary stocks migrate across national waters. Pecl *et al.* (2017) [19] note that shifting species distributions can increase competition among fishing nations and create socio-economic friction over resource access, while altered migration timing affects spawning success and recruitment. Sumaila *et al.* (2011) [24] add an important economic dimension here: because fishing costs, ex-vessel prices, and access rights are all tied to where and when fish are caught, geographic redistribution does not just change biological yield it can directly erode the profitability of established fishing operations even where total catch potential is unchanged. Free *et al.*'s (2019) [8] finding that regional losses are highly uneven some ecoregions losing over a third of their productivity while others see modest gains underscores why climate adaptation in fisheries management increasingly needs to be regionally tailored rather than applied uniformly.

4.2 Aquaculture

Aquaculture is expected to play a growing role in meeting future seafood demand, yet it too is highly exposed to climate change. According to the FAO's *State of World Fisheries and Aquaculture 2024* (FAO, 2024) [1] released as aquaculture production of aquatic animals surpassed capture fisheries output for the first time in history climate change threatens aquaculture productivity by reducing growth performance, increasing production costs, and elevating disease risk, even as the sector's share of global aquatic food production continues to grow. Temperature remains one of the most critical variables governing aquaculture productivity. Species have species-specific optimum thermal ranges; temperatures beyond these limits induce physiological stress, suppress appetite, reduce feed conversion efficiency, and increase mortality. Warm-water systems risk reduced dissolved oxygen during summer months, producing hypoxia and impaired performance, while floods and cyclones damage ponds, cages, and hatcheries sometimes facilitating disease transmission or the escape of cultured stock into surrounding ecosystems.

4.3 Fish physiology and reproduction

Climate change directly affects fish physiology by altering metabolic processes, endocrine regulation, immune responses, and reproduction. Because fish are ectotherms, rising water temperature elevates metabolic rate and oxygen demand while simultaneously reducing oxygen availability. Pörtner (2010) [5] showed that prolonged exposure to elevated temperature can

exceed the aerobic capacity of many species the same oxygen- and capacity-limitation mechanism discussed in Section 2 producing physiological stress and reduced growth. Temperature also regulates gonadal development, gamete maturation, spawning behaviour, and embryonic development; abnormal thermal regimes can disrupt reproductive timing, reduce egg viability, and impair larval survival, with knock-on effects for population resilience.

4.4 Fish health and disease outbreaks

Climate change has measurably increased the occurrence and severity of fish disease. Rising water temperatures favour the proliferation of pathogenic bacteria, viruses, fungi, and parasites while simultaneously suppressing host immune responses. Griffith and Gobler (2020) [25, 22] describe how warming waters act as a co-stressor alongside harmful algal blooms in both marine and freshwater ecosystems, jointly elevating pathogen transmission and disease outbreaks in wild fisheries and aquaculture alike. HAB-associated fish kills driven by both direct toxicity and the hypoxia produced during bloom decomposition have become an increasingly common threat to fisheries production and public health (Gobler, 2020) [22].

4.5 Socio-economic implications for fisheries

Climate-driven declines in fisheries productivity carry substantial socio-economic consequences, particularly in developing countries where fisheries contribute heavily to food security, employment, and rural livelihoods. Allison *et al.* (2009) [26], comparing the climate vulnerability of 132 national economies, found that countries in Central and Western Africa, Peru and Colombia, and parts of tropical Asia (including Bangladesh, Cambodia, Pakistan, and Yemen) are most vulnerable not simply because of the physical exposure to warming, but because of the combined effect of that exposure, the economic and dietary importance of fisheries, and limited societal capacity to adapt. Strikingly, they found that the most vulnerable countries are also among the world's poorest, and rely on fish for roughly twice the share of dietary protein (27%) as less-vulnerable countries (13%) meaning climate impacts on fisheries fall hardest on the populations with the fewest alternatives. Barange *et al.* (2018) [10], in the FAO's technical synthesis on climate impacts across fisheries and aquaculture, echo this finding: millions of small-scale fishers face high vulnerability because their adaptive capacity is constrained by poverty, weak infrastructure, and limited access to technology. Reduced catches raise seafood prices, depress household income, and threaten nutritional security in regions where fish provide the primary source of animal protein precisely the dynamic Allison *et al.* (2009) [26] quantify. According to FAO (2024) [1], the sector as a whole now supports well over half a billion livelihoods worldwide, underscoring the scale of exposure: climate-driven shifts in fish distribution force fishers to travel farther, raising fuel costs and operational risk (Sumaila *et al.*, 2011) [24], and making essential, climate-responsive fisheries management essential to protecting both livelihoods and long term food security.

5. Adaptation strategies for climate-resilient fisheries and aquatic ecosystems

Climate change is now an unavoidable feature of fisheries management, making adaptation as essential as mitigation. While mitigation targets the reduction of greenhouse gas emissions, adaptation aims to minimise the adverse effects of climate change already in motion, by strengthening the

resilience of aquatic ecosystems, fisheries resources, and the communities that depend on them. Barange *et al.* (2018) ^[10], in FAO's technical synthesis on climate impacts on fisheries and aquaculture, argue that effective adaptation must integrate ecological conservation, technological innovation, sustainable management, and socio-economic planning if it is to reduce vulnerability while sustaining productivity and food security. The FAO's most recent flagship assessment (FAO, 2024) ^[1] reinforces this, framing climate-resilient fisheries as dependent on ecosystem-based management, stronger governance, sustained scientific monitoring, and genuine stakeholder participation.

5.1 Climate-smart fisheries and aquaculture

Climate-smart fisheries and aquaculture (CSFA) is an integrated approach aimed at raising productivity while strengthening resilience and reducing environmental impact under a changing climate. Barange *et al.* (2018) ^[10] describe climate-smart approaches as combining improved resource-use efficiency, environmentally friendly production technologies, better disease management, and reduced greenhouse gas emissions across the fisheries value chain. In aquaculture specifically, this translates into improved water-quality management, optimised feeding strategies, diversification of cultured species, integrated farming systems, and low-carbon technology adoption measures that raise production efficiency even as they reduce environmental degradation. A recent systematic review by Soudah *et al.* (2026) ^[27], covering 90 studies from West and Central Africa, similarly identifies recirculating systems, biofloc technology, and integrated aquaculture–agriculture models as the climate-smart practices with the strongest combined productivity, adaptation, and mitigation performance, though the review notes a persistent gap between their technical potential and real-world uptake. Ahmed and Solomon (2016) ^[28] make a comparable case for climate-smart aquaculture as a route to stabilising fish production in Nigeria against the backdrop of shifting hydrological regimes and increasingly frequent flood and drought events.

5.2 Ecosystem-based fisheries management (EBFM)

Where traditional fisheries management focuses on individual target species, Ecosystem-Based Fisheries Management (EBFM) considers the full web of interactions among species, habitats, environmental variables, and human activity. Pikitch *et al.* (2004) ^[29], in the foundational statement of this approach, argued that maintaining ecosystem structure, biodiversity, and ecological processes is what ultimately sustains fisheries productivity over the long term, not narrower, single-species optimisation. Climate change makes this broader view increasingly necessary, since fish stocks are continuously redistributing themselves geographically and ecologically (Cheung *et al.*, 2013; Pecl *et al.*, 2017) ^[13, 19]. EBFM responds by incorporating habitat conservation, biodiversity protection, environmental monitoring, and adaptive harvest regulation, while protecting nursery habitats mangroves, estuaries, seagrass meadows, and coral reefs that underpin fish recruitment and biodiversity (Alongi, 2015; Hoegh-Guldberg *et al.*, 2017) ^[18, 17]. Marine protected areas function as a complementary tool within this framework, since short-term ocean forecasts allow managers to anticipate and monitor ecosystem stress such as coral bleaching and track subsequent recovery, thereby helping assess the effectiveness of conservation measures (Hartog *et al.*, 2023) ^[30].

5.3 Sustainable aquaculture technologies

Technological innovation is central to improving aquaculture's resilience under climate change. Recirculating Aquaculture Systems (RAS) offer greater environmental control by continuously treating and reusing water, reducing both dependence on external water sources and disease transmission risk. Integrated Multi-Trophic Aquaculture (IMTA) combines finfish, shellfish, and seaweed production to improve nutrient recycling and reduce waste accumulation, while biofloc technology converts nitrogenous waste into microbial protein usable by cultured fish and shrimp improving water quality and feed efficiency simultaneously (FAO, 2024; Ogello *et al.*, 2024) ^[1, 31]. Abisha *et al.* (2022) ^[32] add that IMTA also helps buffer culture-based fisheries against salinity and temperature stress, since shellfish and seaweed components filter excess nutrients and moderate water temperature, making the approach particularly valuable in coastal and brackish-water systems exposed to climatic variability.

5.4 Conservation and habitat restoration

Healthy habitats provide the most fundamental form of climate resilience. Mangrove forests, wetlands, coral reefs, floodplains, and seagrass meadows function as nursery grounds and natural coastal barriers while sequestering carbon. Alongi (2015) ^[18] shows that mangrove restoration enhances fisheries productivity and protects coastal communities from storm surge, while also contributing disproportionately to bluecarbon storage relative to the area mangroves occupy. Coral reef restoration through transplantation, artificial reef deployment, and marine protected areas can support post-bleaching recovery, complementing the broader picture that Hoegh-Guldberg *et al.* (2017) ^[17] present of reefs under mounting thermal and acidification stress.

5.5 Early warning systems and climate information services

Timely climate information allows fishers and aquaculture farmers to anticipate risk rather than simply react to it. Early warning systems integrate meteorological forecasts, oceanographic observation, satellite monitoring, and hydrological modelling to flag cyclones, marine heatwaves, floods, droughts, harmful algal blooms, and disease outbreaks before they cause maximum damage directly relevant given how Gobler (2020) ^[22] and Griffith and Gobler (2020) ^[25] describe HABs and disease as compounding, climate-linked costressors. According to FAO (2024) ^[1], such information services let producers adjust harvesting schedules, stocking densities, and feeding practices to reduce losses during extreme events. Hobday *et al.* (2016) ^[33] demonstrate that seasonal forecasting, already applied operationally to salmon farming and tuna fisheries, can extend this warning window to several months ahead, giving marine industries time to adjust before an event materialises rather than simply responding after the fact. The World Meteorological Organization's regional assessment (WMO, 2026) ^[34] underscores that the value of such systems depends on last-mile delivery alerts must be timely and trusted to reach the small-scale fishers and coastal communities most exposed to risk. At the farm level, machine-learning-based warning tools are also emerging for disease specifically: Xie *et al.* (2025) ^[35] developed a predictive system for cryptocaryoniasis outbreaks in marine aquaculture using oceanographic and meteorological variables, illustrating how climate information services are beginning to extend from broad hazard forecasting into pathogen-specific early warning.

5.6 Genetic improvement and selective breeding

Genetic improvement offers a longer-horizon route to climate resilience in aquaculture. Selective breeding has already produced strains with improved growth, feed efficiency, disease resistance, and thermal tolerance. [Houston et al. \(2020\)](#) ^[36], reviewing the state of aquaculture genomics, describe how genomic tools including marker-assisted and genomic selection have accelerated breeding programmes for several commercially important species by improving resistance to infectious disease and environmental stressors, positioning genomics as an increasingly central tool for climate-resilient aquaculture. [Abisha et al. \(2022\)](#) ^[32] similarly emphasise species diversification and selective breeding, alongside IMTA and RAS, as among the most widely adopted adaptation strategies for abiotic climate stress across freshwater, brackish, and coastal aquaculture systems.

5.7 Community-based adaptation and policy support

Technology alone cannot deliver climate resilience without

effective governance and community buy-in. Community-based fisheries management encourages local stakeholders to participate in conservation, restoration, and sustainable harvesting, improving regulatory compliance while incorporating indigenous and local knowledge into adaptation planning (Table 3). [Barange et al. \(2018\)](#) ^[10] note that this is particularly critical for small-scale fishers, whose adaptive capacity is often constrained by poverty and limited infrastructure. National policy should accordingly integrate climate adaptation through stronger institutional coordination, research investment, capacity building, insurance mechanisms, and financial support reinforced internationally through frameworks such as the Paris Agreement and the Sustainable Development Goals, both of which [FAO \(2024\)](#) ^[1] identifies as central to the sector's Blue Transformation agenda. This policy dimension is increasingly visible at the national level: [Soudah et al. \(2026\)](#) ^[27] point to sectoral National Adaptation Plans, such as Senegal's Aquatic Food Sector NAP, and comprehensive frameworks such as Ghana's Fisheries and Aquaculture Bill and Sustainable Ocean Plan, as examples of countries translating climate-resilient fisheries principles into binding domestic policy instruments.

Table 3: Climate Change Adaptation Strategies for Sustainable Fisheries and Aquaculture

Adaptation Strategy	Key Components	Expected Benefits
Climate-smart fisheries and aquaculture	Efficient resource use, sustainable farming practices, improved water quality management	Enhanced productivity and climate resilience
Ecosystem-based fisheries management (EBFM)	Habitat conservation, adaptive harvest regulations, biodiversity protection	Sustainable fish stocks and ecosystem stability
Sustainable aquaculture technologies	Recirculating Aquaculture Systems (RAS), Biofloc Technology (BFT), Integrated Multi-Trophic Aquaculture (IMTA)	Improved water quality, reduced environmental impacts and disease risk
Habitat conservation and restoration	Mangrove restoration, coral reef conservation, wetland protection	Improved biodiversity and fish recruitment
Early warning systems	Weather forecasting, disease surveillance, climate information services	Reduced production losses from extreme events
Genetic improvement	Selective breeding and genomics	Development of climate-tolerant and disease-resistant fish strains
Community participation and policy support	Capacity building, financial assistance, stakeholder engagement	Strengthened adaptive capacity and sustainable resource management

6. Sustainable Management of Fisheries Resources under Climate Change: The mounting impacts of climate change on aquatic ecosystems and fisheries call for a shift away from conventional, single-species resource management toward adaptive, ecosystem-based approaches. Sustainable fisheries management aims to hold fish stocks at biologically sustainable levels while conserving aquatic biodiversity, ecosystem function, and the livelihoods dependent on them. Climate change compounds the uncertainty inherent in this task by altering species distributions, productivity, recruitment, and habitat availability, which means management strategies must become markedly more flexible and climate-responsive if they are to remain effective ([FAO, 2024](#)) ^[1].

6.1 Ecosystem-based fisheries management

Ecosystem-Based Fisheries Management (EBFM) has become one of the most effective frameworks for sustaining fisheries under a changing climate. Unlike single-species management, EBFM accounts for ecological interactions among fish populations, habitats, predators, prey, and environmental drivers, alongside the human dimensions of fisheries. [Pikitch et al. \(2004\)](#) ^[29] argued that maintaining ecosystem integrity and biodiversity is fundamental to sustaining fisheries productivity over the long term a principle that becomes more urgent, not less, as climate change reshuffles species distributions ([Cheung](#)

[et al., 2013](#); [Pecl et al., 2017](#)) ^[13, 19]. Under climate change, EBFM promotes adaptive harvest strategies, habitat conservation, protection of spawning grounds, and restoration of degraded ecosystems. Continuous monitoring of environmental indicators water temperature, dissolved oxygen, salinity, and primary productivity allows managers to adjust harvest regulations as ecosystem conditions shift, improving stock resilience and reducing the risk of overexploitation compounding climate stress.

6.2 Conservation of critical aquatic habitats

Healthy aquatic habitats underpin both fisheries productivity and biodiversity. Mangroves, coral reefs, seagrass meadows, estuaries, wetlands, and floodplains provide spawning grounds, nursery habitat, feeding areas, and refuge for commercially important species yet climate change is accelerating their degradation through warming, sea-level rise, acidification, coastal erosion, and extreme weather ([Hoegh-Guldberg et al., 2017](#)) ^[17]. [Alongi \(2015\)](#) ^[18] shows that conserving and restoring mangrove forests enhances fisheries production while simultaneously improving shoreline protection and carbon sequestration a rare case where a single intervention delivers both adaptation and mitigation benefits. Restoration of coral reefs and seagrass ecosystems similarly supports biodiversity conservation while strengthening the adaptive capacity of

coastal fisheries, and wetland restoration improves hydrological regulation, nutrient cycling, and water quality for freshwater fisheries.

6.3 Science-based fisheries assessment and monitoring

Reliable scientific data underpins effective fisheries management under climate change. Long-term monitoring programmes provide the stock-dynamics, biodiversity, habitat-quality, and environmental data that stock assessments and management decisions depend on. [FAO \(2024\)](#) ^[1] emphasises that integrating fisheries-dependent and fisheries-independent surveys with environmental monitoring materially improves stock assessments and supports evidence-based decisions. Advances in remote sensing, satellite observation, acoustic surveys, environmental DNA (eDNA), and geographic information systems (GIS) have substantially expanded the capacity to monitor aquatic ecosystems at regional and global scales, enabling near-continuous assessment of habitat change, fish distribution, harmful algal blooms, and oceanographic conditions and, in turn, more timely management intervention.

6.4 Sustainable harvesting and stock enhancement

Keeping exploitation within biologically sustainable limits remains a core objective of fisheries management, but climate change complicates this by reducing recruitment success and altering stock productivity in ways that require periodic revision of harvest control rules a dynamic directly evidenced by [Free *et al.*'s \(2019\)](#) ^[8] finding that regional MSY losses under warming range from negligible to over 30%. Adaptive catch quotas, seasonal closures, minimum legal size regulations, and protection of spawning aggregations all help maintain reproductive capacity under this shifting baseline. Stock enhancement programmes, including hatchery-based restocking, can contribute to rebuilding depleted populations when grounded in sound genetic and ecological principles including the kind of genomic tools reviewed by [Houston *et al.* \(2020\)](#) ^[36] for identifying resilient strains. However, [FAO \(2024\)](#) ^[1] stresses that stock enhancement should complement, not substitute for, habitat conservation and sustainable management.

6.5 Community participation and co-management

Active community participation is increasingly central to sustainable fisheries governance. Community based management promotes stakeholder involvement in planning, decision-making, monitoring, and enforcement, improving regulatory compliance, while indigenous and traditional ecological knowledge often supplies valuable information on seasonal fish movements and environmental change that complements formal scientific observation. Co-management arrangements involving governments, researchers, fishers, and local organisations have demonstrated improved conservation outcomes and greater community resilience under climate variability echoing the community-level emphasis [Barange *et al.* \(2018\)](#) ^[10] place on small-scale fishers' adaptive capacity.

6.6 Policy integration and international cooperation

Because climate impacts on fisheries frequently cross national boundaries, coordinated international action is essential. Global frameworks the FAO Code of Conduct for Responsible Fisheries, the Paris Agreement, the Convention on Biological Diversity, the Kunming–Montreal Global Biodiversity Framework, and the UN Sustainable Development Goals (notably SDG 2, SDG 13, and SDG 14) provide overlapping

policy scaffolding for sustainable fisheries management. FAO's Blue Transformation initiative ([FAO, 2024](#)) ^[1] further promotes sustainable aquaculture expansion, stronger fisheries management, and resilient aquatic food systems, and national governments are encouraged to strengthen research capacity, climate information services, resilient infrastructure, and financial support for vulnerable fishing communities.

6.7 Emerging technologies for sustainable fisheries

Recent technological advances are transforming fisheries management by improving environmental monitoring, stock assessment, and decision-making. Artificial intelligence, machine learning, IoT-based sensor networks, autonomous underwater vehicles, drones, and big-data analytics all enable near real-time monitoring of aquatic ecosystems and fish populations. Environmental DNA has emerged as a powerful, non-invasive tool for biodiversity assessment and early detection of invasive species directly relevant to the invasion pathways [Rahel and Olden \(2008\)](#) ^[23] identify as expanding under climate change. Blockchain technology, meanwhile, is improving seafood traceability and sustainability certification across supply chains. Integrating these digital technologies with ecosystem-based management is likely to substantially improve adaptive capacity as climate impacts on fisheries continue to intensify.

7. Government policies and international initiatives

Climate change adaptation and sustainable fisheries management require coordinated policy action at global, regional, and national levels. International agreements and national programmes together provide the strategic scaffolding for conserving aquatic ecosystems, building climate resilience, and ensuring the sustainable use of fisheries resources.

7.1 Paris agreement

The Paris Agreement, adopted under the United Nations Framework Convention on Climate Change (UNFCCC) in 2015, aims to limit the increase in global average temperature to well below 2 °C above preindustrial levels while pursuing efforts to limit warming to 1.5 °C.. Although the agreement does not specifically target fisheries, its mitigation and adaptation objectives are fundamental for protecting aquatic ecosystems from ocean warming, acidification, and sea-level rise. Through Nationally Determined Contributions (NDCs), countries are encouraged to integrate fisheries and aquaculture into national climate adaptation strategies ([UNFCCC, 2015](#); [Gaines *et al.*, \(2018\)](#) ^[37, 38]).

7.2 United nations sustainable development goals (SDGs)

The 2030 Agenda for Sustainable Development recognizes fisheries and aquatic ecosystems as integral components of sustainable development. SDG 2 (Zero Hunger), SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land) collectively promote sustainable fisheries, biodiversity conservation, ecosystem restoration, and climate resilience. Recent studies further demonstrate that achieving these goals requires climate-adaptive fisheries management and ecosystem-based governance ([United Nations, 2015](#); [Free *et al.*, \(2020\)](#) ^[39, 2]).

7.3 FAO initiatives and blue transformation

The Food and Agriculture Organization (FAO) promotes climate-resilient fisheries through scientific assessments, policy guidance, and capacity-building. Its Blue Transformation

initiative aims to expand sustainable aquaculture, improve fisheries management, reduce post-harvest losses, and strengthen aquatic food value chains. The *State of World Fisheries and Aquaculture 2024* reports that aquaculture surpassed capture fisheries in aquatic animal production for the first time, highlighting the importance of sustainable aquatic food systems. Scientific evidence also indicates that adaptive fisheries management can substantially reduce climate-related impacts on fisheries (FAO, 2022, 2024; Free *et al.*, 2020) ^[12, 21].

7.4 Convention on biological diversity (CBD)

The Convention on Biological Diversity (CBD) provides the global framework for biodiversity conservation, sustainable use of biological resources, and equitable benefit-sharing. During COP15, Parties adopted the Kunming–Montreal Global Biodiversity Framework, including the "30×30" target to conserve at least 30% of terrestrial, inland water, coastal, and marine ecosystems by 2030. These biodiversity conservation measures directly strengthen ecosystem resilience and support sustainable fisheries management (Convention on Biological Diversity, 2022; Díaz *et al.*, 2019) ^[40, 41].

7.5 Ramsar convention on wetlands

The Ramsar Convention promotes the conservation and wise use of wetlands, which provide critical ecosystem services including flood regulation, carbon sequestration, water purification, and nursery habitats for numerous fish species. Wetland conservation enhances ecosystem resilience to climate change while sustaining inland fisheries and biodiversity. Scientific assessments further indicate that wetland restoration is essential for maintaining freshwater ecosystem services under changing climatic conditions (Ramsar Convention Secretariat, 2018; Davidson, 2014) ^[42].

7.6 IPCC assessments

The Intergovernmental Panel on Climate Change (IPCC) provides the scientific foundation for understanding climate change impacts on aquatic ecosystems. The AR6 Working Group II assessment reports that ocean warming, acidification, deoxygenation, and extreme weather events are already affecting fisheries worldwide. It recommends ecosystem-based adaptation, habitat restoration, climate-smart fisheries, and adaptive governance to enhance resilience (IPCC, 2022; Cooley *et al.*, 2022) ^[4].

7.7 National fisheries policy and PMMSY (India)

India has incorporated climate resilience into fisheries development through the Pradhan Mantri Matsya Sampada Yojana (PMMSY), launched in 2020. The programme promotes sustainable aquaculture, fisheries infrastructure, biosecurity, aquatic animal health, and climate-resilient technologies such as Recirculating Aquaculture Systems (RAS), biofloc, and aquaponics. PMMSY also supports resource conservation, valuechain development, and livelihood enhancement among fishers. Recent scientific studies emphasize that policy-driven climate adaptation and technological innovation are essential for improving the resilience of Indian fisheries and aquaculture (Department of Fisheries, Government of India, 2020) ^[43].

7.8 ICAR initiatives

The Indian Council of Agricultural Research (ICAR), through institutes such as ICAR-CIFE, ICAR-CIFRI, and ICAR-CMFRI, undertakes research on climate-resilient aquaculture, aquatic animal health, biodiversity conservation, selective

breeding, and ecosystem restoration. These institutions develop climate adaptation technologies, provide scientific support for fisheries policies, and strengthen national capacity for sustainable fisheries management. Their research complements national fisheries policies by promoting evidence-based adaptation strategies (ICAR, 2023; CMFRI, 2023; Barange *et al.*, 2018) ^[10].

8. Knowledge gaps and future research needs

Despite substantial progress in understanding how climate change affects aquatic ecosystems and fisheries, several scientific and management challenges remain unresolved. Addressing these gaps is essential for developing effective adaptation strategies and evidence-based policy.

8.1 Lack of long-term datasets

Reliable long-term environmental and fisheries datasets remain limited in many regions, particularly in developing countries. Cooley *et al.* (2022) ^[4] note that continuous monitoring of water quality, biodiversity, fish populations, and ecosystem processes is essential for improving climate-impact assessments and supporting adaptive fisheries management yet such monitoring infrastructure remains patchy outside wellresourced regions, limiting the precision of assessments in exactly the areas most dependent on small-scale fisheries.

8.2 Limited understanding of tropical fisheries

Most climate change research to date has focused on temperate marine ecosystems, while tropical freshwater and coastal fisheries remain comparatively understudied despite their high biodiversity and outsized socio-economic importance. Barange *et al.* (2018) ^[10] identify this as a persistent gap in the FAO's global synthesis of climate impacts, and additional research is needed to characterise climate vulnerability, adaptive capacity, and ecosystem responses specifically in tropical regions, where reliance on fisheries for protein and livelihoods is often highest.

8.3 Disease prediction under climate change

Rising temperatures and environmental variability are altering pathogen dynamics and disease emergence in aquatic organisms, yet predictive models linking climatic variables to disease outbreaks remain underdeveloped. Building on the co-stressor dynamics that Griffith and Gobler (2020) ^[25, 22] describe between warming and harmful algal blooms, improved disease surveillance, molecular diagnostics, and climateinformed forecasting systems are needed to reduce production losses across fisheries and aquaculture a priority the FAO (2024) ^[1] also flags as central to protecting future aquatic food security.

8.4 Species-specific adaptation mechanisms

Aquatic species vary considerably in physiological tolerance, genetic diversity, and adaptive capacity, and the OCLTT framework that Pörtner (2010) ^[5] developed while foundational does not resolve how individual species differ in their capacity to acclimate or adapt over successive generations. More research combining genomic and physiological approaches is needed to identify which species are genuinely climate-resilient and to clarify the mechanisms underlying thermal tolerance, reproductive adaptation, and disease resistance, building on the selective-breeding groundwork that Houston *et al.* (2020) ^[36] describe for aquaculture species.

8.5 Uncertainty in climate models

Although climate models have improved substantially since the IPCC's earlier assessment cycles, meaningful uncertainty remains around regional climate projections, extreme-event frequency, and ecosystem-level responses to compound stressors. Integrating higher-resolution climate models with ecological and socio-economic data the kind of integration Cooley *et al.* (2022) ^[4] call for in the AR6 WGII assessment would improve both the precision of future projections and the practical usefulness of adaptive management decisions built on them.

8.6 Economic valuation of climate impacts

Comprehensive economic assessments of climate-induced losses in fisheries, ecosystem services, and biodiversity remain limited, even as Free *et al.* (2019) ^[8] demonstrate that regional productivity losses can already reach 15–35% in some ecoregions. Future research should quantify the economic costs of habitat degradation, declining fish stocks, disease outbreaks, and adaptation measures themselves, so that policymakers can direct limited resources toward the most cost-effective interventions rather than relying on ecological findings alone to justify investment decisions.

9. Conclusion

Climate change is fundamentally reshaping aquatic ecosystems and fisheries through rising water temperatures, ocean acidification, deoxygenation, sea-level rise, and increasing climatic extremes. These interconnected stressors alter ecosystem structure and function, reduce biodiversity, impair fish health and productivity, and threaten the sustainability of capture fisheries and aquaculture. The resulting ecological and socio-economic impacts underscore the vulnerability of aquatic food systems, particularly in regions that depend heavily on fisheries for food security and livelihoods. Building climate resilience requires the integration of climate-smart aquaculture, ecosystem-based fisheries management, habitat restoration, sustainable production technologies, and science-based policy frameworks. Advances in environmental monitoring, genomics, selective breeding, and climate-informed decision support systems will further strengthen adaptive capacity. However, significant knowledge gaps remain regarding long-term ecosystem responses, climate–disease interactions, and the resilience of tropical fisheries. Future research should prioritize interdisciplinary approaches that integrate ecological, technological, and socio-economic perspectives to support evidence-based management. Such coordinated efforts will be essential to conserve aquatic biodiversity, enhance fisheries resilience, and ensure sustainable aquatic food production under a changing climate.

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