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REVIEW ARTICLE

Climate change effects on aquaculture production and its sustainable management through climate-resilient adaptation strategies: a review

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Abstract

Aquaculture witnessed a remarkable growth as one of the fastest-expanding sector in the food production industry; however, it faces serious threat from the unavoidable impacts of climate change. Understanding this threat, the present review explores the consequences of climate change on aquaculture production and provides need based strategies for its sustainable management, with a particular emphasis on climate-resilient approaches. The study examines the multi-dimensional impacts of climate change on aquaculture which includes the shifts in water temperature, sea-level rise, ocean acidification, harmful algal blooms, extreme weather events, and alterations in ecological dynamics. The review subsequently investigates innovative scientific interventions and climate-resilient aquaculture strategies aimed at strengthening the adaptive capacity of aquaculture practices. Some widely established solutions include selective breeding, species diversification, incorporation of ecosystem-based management practices, and the implementation of sustainable and advanced aquaculture systems (aquaponics and recirculating aquaculture systems (RAS). These strategies work towards fortifying aquaculture systems against climate-induced disturbances, thereby mitigating risks and ensuring sustained production. This review provides a detailed insight to the ongoing discourse on climate-resilient aquaculture, emphasizing an immediate need for prudent measures to secure the future sustainability of fish food production sector.

Keywords Climate change · Global warming · Climate-resilient · Mitigation · Sustainability

Introduction

The aquaculture industry has well established itself as a significant food production sector over the past 20 years, meeting a sizeable percentage of the need for animal protein across all populations, regardless of their style of living. The amount of fish produced through aquaculture has increased steadily, reaching 82.1 million tons (46%) of the total 179 million tons of fish produced worldwide. In addition, it is predicted that aquaculture output would represent 53% of all fish produced globally by 2030, up from the current 46% (FAO 2020). The most pressing concern is whether the sector is growing quickly and sustainably enough to meet anticipated demand, which is being made worse by a changing climate and a rapidly growing population (Maulu et al. 2021). In recent years, there has been increasing evidence that climate change and increased variability, including extreme events such as floods and droughts, can significantly impact water quality around the world (Kundzewicz et al. 2007; Park et al. 2010). The effects of climate change on

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human health and aquatic ecosystems can be observed in the degradation of water quality as a result of higher water temperatures, increased precipitation intensity, and longer periods when there are low flows caused by higher temperatures (Kundzewicz et al. 2007). As a consequence of climate change, both the qualities, as well as the quantity of food production are under threat (Myers et al. 2017; Hamdan et al. 2015). A range of climate variables can affect human food needs and food production in the future, and the impact of such climate variations is of the utmost concern for many developing countries, especially those in poverty (Ahmed et al. 2019). In the wake of the publication of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, the hazards posed by climate change to human society and its natural resources have been given major attention (IPCC 2007). It has become evident through recent occurrences that both semi-arid and arid regions are becoming drier as the amplitude and unpredictability of rainfalls and storms increase. In addition, both semi-arid and arid regions show a tendency towards greater extremes (IPCC 2007).

In recent years, climate change impacts have gained considerable attention, in part due to the significance of aquaculture's contribution to global food security, nutrition, and livelihoods due to the sector’s significant contribution to international trade (Maulu et al. 2021; Blanchard et al. 2017; Dabbadie et al. 2019). Currently, the aquaculture industry is highly dependent on the climate, and therefore, climate change could pose a threat to the industry’s ability to grow and produce fish in the future (FAO 2020). The warming of the surface waters of the oceans and inland waters, as well as the rise in sea levels and the melting of the ice, are expected to negatively affect many fish species in the future (Dervash et al. 2023). As a result of global warming, some marine species are already migrating to high latitudes, but other species, such as those found in the Arctic and freshwater, have nowhere to go and are in danger of extinction (Dahms and Killen 2023). It is also worth mentioning that the oceans are absorbing increasing quantities of CO_2 that is causing acidification which has an important impact on marine life in the ocean (Sun 2023).

Many scientific studies and analyses are used to evaluate climate change, which is defined as a change in weather through time that results from either natural variability or human action (Dey and Mishra 2017). Given that climate change is a biophysical process, the aquatic system and the resources as a whole could be affected in a variety of physical and ecological ways. Such information and analysis show that these elements produce greenhouse gases that tend to shade the globe, resulting in the thinning of the ozone layer, global warming, and flooding (MacNeill et al. 1991; FAO 2020). Anticipated consequences include an escalation in the frequency and intensity of droughts, floods, and other extreme weather events, placing additional strain on water supplies, food security, health, infrastructure, and overall developmental efforts. These factors collectively pose a substantial risk to the stability and productivity of aquaculture operations worldwide. The aim of this study was to provide valuable insights into climate-smart options that can enhance the sustainability of aquaculture. This includes identifying and evaluating strategies and practices that enable aquaculture systems to adapt to and mitigate the impacts of climate change. By synthesizing existing knowledge and exploring new approaches, the study aims to offer actionable recommendations for sustainable aquaculture management in the face of changing climatic conditions.

The significance of this study lies in its potential to guide policymakers, researchers, and practitioners toward evidence-based strategies for mitigating the adverse effects of climate change on aquaculture. By understanding the vulnerabilities and adopting resilient approaches, the aquaculture sector can not only adapt to ongoing changes but also contribute to global food security in the face of a changing climate. As climate change continues to accelerate, the insights gained from this study will be instrumental in fostering the sustainability and resilience of aquaculture systems worldwide.

The effects of climate change on aquaculture production system

Climate change manifests both direct and indirect impacts on aquaculture production, influencing the sector in both the short term and long term (Maulu et al. 2021). Table 1 provides a summary of diverse climate change elements and their corresponding impacts on aquaculture. Climate change outcomes such as rising temperature, ocean acidification, harmful algal blooms, etc. can directly affect the physical and physiological characteristics of finfish and shellfish (Handisyde et al. 2006; De Silva and Soto 2009). These changes may manifest in lower productivity, sudden deaths, and shifts in spawning seasons and quantities among the effects of climate change on aquaculture (McIlgorm et al. 2010; Ho et al. 2016).

The challenges faced by aquaculture production and sustainability due to climate change are illustrated in Fig. 1. Over recent decades, the accumulation of greenhouse gases in the atmosphere has triggered notable transformations in various facets of Earth’s climate, oceans, coasts, and freshwater ecosystems. These changes encompass alterations in the temperature of air and water, shifts in rainfall patterns, fluctuations in sea level, modifications in ocean acidity, adjustments to wind patterns, and variations in the intensity of tropical cyclones (Leng et al. 2023). These changes have an impact on fisheries and aquaculture (Cochrane et al.

Table 1 Summary of the various elements of climate change and their negative effects on aquaculture production

S. no	Elements/stressor	Impact of elements	References
	Raising temperature	Poor growth and survival of cold-water species, Water quality deterioration, affects the physiology, growth patterns, and behavior of aquatic organisms thermal stratification, damage the gonads	Adhikari et al. (2018) Zhang et al. (2019) Mitra et al. (2023) Asch et al. (2019) Miranda et al. (2013)
	Ocean acidification	Reduced species growth performance and survival, Increased water acidity levels Poor coral skeleton development for shell-forming species	Richards et al. (2015) Whiteley (2011)
	Harmful algal blooms	Impacts marine aquaculture Deterioration of water quality	Lenzen et al. (2021)
	Disease	Increased production costs due to disease outbreaks	Collins et al. (2020) Khalid (2022) Gubbins et al. (2013)
	Changes in rainfall/precipitation patterns	Droughts could increase production costs Flooding may increase the loss of organisms in lowland areas Destruction of production facilities	Loo et al. (2015) Bell et al. (2010)
	Sea level rise and salinity intrusion	Destruction of several coastal ecosystems, and possible intrusion of saline water into freshwater systems and culture facilities in some regions, may affect species richness, abundance and distribution, and phonological shifts	Kibria et al. (2017) De Silva and Soto (2009)

2009). The dissemination and output of marine and freshwater species are changing due to climate change, which is also having an impact on biological processes and changing food webs. Uncertainty exists over the effects on aquatic ecosystems, fisheries, aquaculture, and the people that depend on them (Yazdi and Shakouri 2010).

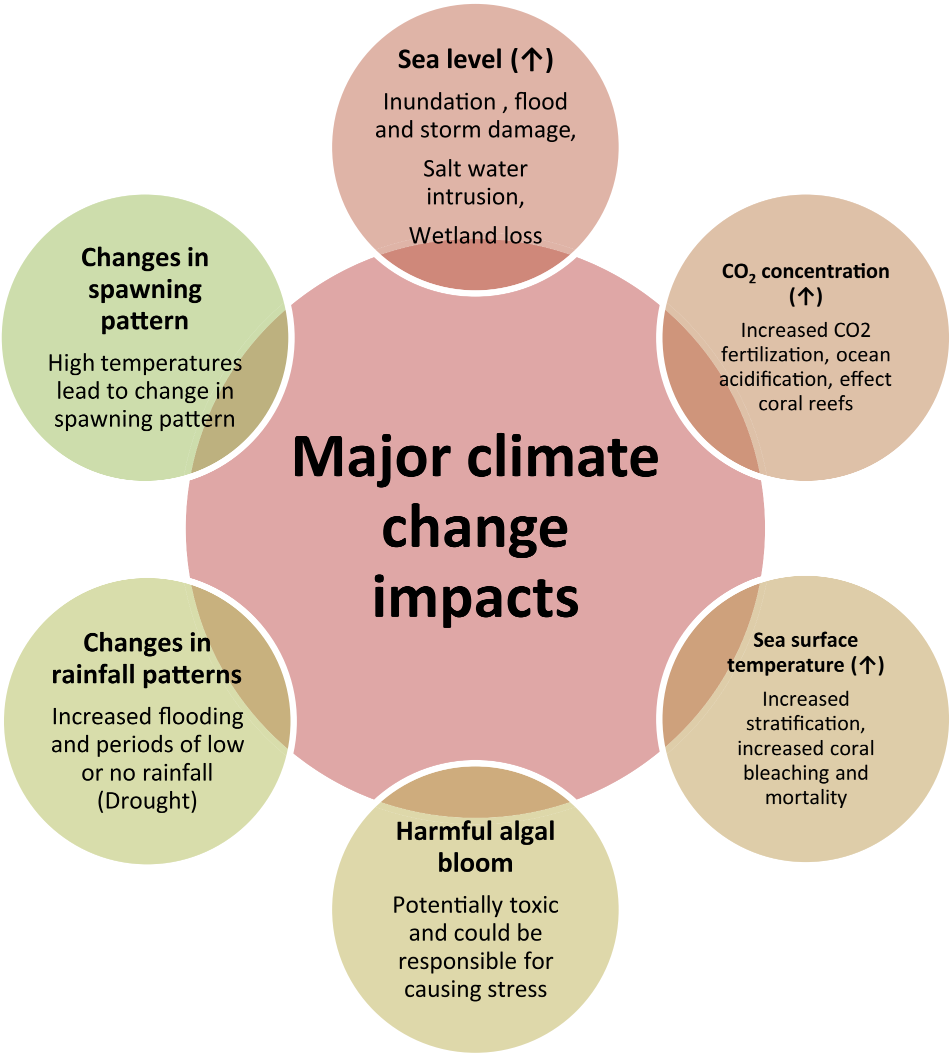
Raising temperature

Fish, as well as aquatic invertebrates, are among the aquatic organisms that are all poikilothermic, which means their internal temperatures fluctuate concerning the ambient temperature in the water. Hence, they are extremely sensitive to changes in the ambient temperature outside of their usual habitat, which plays a major role in their survival (Roessig et al. 2004; Adhikari et al. 2018). It is projected that many species of finfish and shellfish, as well as their metabolism, physiology, eating habits, and growth performance will be affected as well (Zhang et al. 2019; Lemasson et al. 2018). There is no doubt that global warming and temperature rise have adverse effects on pond aquaculture. There is evidence that rising temperatures in freshwater ponds could adversely affect the ecosystem, including changes in the way the ponds function as an ecosystem (Woodward et al. 2010). Global warming can cause rapid growth of heat-tolerant cyanobacteria in ponds, leading to severe eutrophication due to higher temperatures and contamination (Kumar and Padhy 2015). Massive cyanobacteria blooms in eutrophic ponds reduce diversity, affecting even other cyanobacteria species (Elayaraj and Selvaraju 2014). Higher temperatures, such as those caused by the Urban Heat Island (UHI) effect, may significantly alter the growing season for aquatic organisms, as observed in streams (Nelson & Palmer 2007). Ficke et al. (2007) reported that it may be possible to cause sub-lethal physiological effects on tropical fish by a small increase in water temperature (1–2 °C). According to De Silva and Soto (2009), rises in water temperatures above 17 °C can adversely impact salmon aquaculture. These effects may include increased vaporization and cloud cover, leading to a reduction in solar radiation reaching the ponds. Consequently, this can exacerbate issues such as algae blooms and red tides.

Impact of rising temperature on aquatic animal health

As the temperature fluctuates, it is likely that bacterial, parasitic, viral, as well as fungal infections that affect aquaculture will be affected in unpredictable ways (Lieke et al. 2020). Heat stress makes cultured animals more susceptible to illness, and rising temperatures may encourage the spread of exotic diseases (Collins et al. 2020; Khalid 2022). Fish and their diseases can be directly impacted by increases in water temperature; however, multivariate environmental change may have unpredictable effects on both. Depending on the overall effects of all three connected components, the incidence and severity of the disease may rise, fall, or simply fluctuate in time and space (Chiaramonte et al. 2016). Most likely, climate change will have an impact on disease emergence by increasing the frequency of some diseases in existing geographic areas and their arrival in new ones. The possibility of the establishment and spread of exotic parasites and pathogens will likely grow as a result of climate change,

Fig. 1 Major climate change impact on aquaculture and coastal ecosystem



which is also anticipated to affect the aquatic environment and boost drivers for the introduction of exotic fish species (Kibria et al. 2021). Numerous finfish and shellfish species are projected to experience an increase in the replication rate, pathogenicity, length of life cycles, and transmission of infections when the temperature rises (Sae-Lim et al. 2017).

Variable climate stresses fish, which makes infections easier to spread. According to Sonone et al. (2020), it is possible that in freshwater aquaculture, filter-feeding mollusks may be more likely to absorb toxicants and heavy metals due to accelerated metabolic rates brought on by higher temperatures. This could affect food safety regulations and certification difficulties. In numerous marine taxa, including corals, echinoderms, mammals, mollusks, and turtles, disease outbreaks have grown over the past three decades on a global scale (Ward and Lafferty 2004). The temperature elevation has been associated with an incidence of several emerging diseases in aquatic animals (Chiaramonte et al. 2016; Barange and Perry 2009; Harvell et al. 2002). As long as the other pathogen-specific requirements for transmission are met, temperature encourages the growth and infection of additional hosts (Karvonen et al. 2010). Through changes in the distribution of hosts or pathogens, previously unknown diseases have also appeared in new locations, many of which are in response to climate change (Harvell et al. 1999).

Rising temperatures may also speed the spread of epizootic diseases in aquaculture, raising serious economic issues. Epizootic disease outbreaks are already one of the biggest obstacles preventing aquaculture production systems from being successful in many regions of the world (Marcogliese 2008; Maulu et al. 2021). The host-parasite relationship between salmonid fish and *Tetracapsuloides bryosalmonae* is highly sensitive to temperature changes. Higher temperatures can have numerous negative effects on the host at various levels. Some of these effects include the production of parasite spores by the bryozoan host, fish infection rates with *T. bryosalmonae*, and activation of the fish immune system, resulting in the emergence of proliferative kidney disease

(PKD) symptoms (Bruneaux et al. 2017). The ecological features of each disease have a major impact on the direction and breadth of changes in disease occurrence, according to research on the effects of global warming on fish diseases. The prevalence of some infections may decrease or remain unchanged, even though some viruses benefit from global warming (Karvonen et al. 2010). A rapid increase in daily temperatures at the beginning of summer may lead to higher population of *V. vulnificus* in fish pond water (Paz et al. 2007; Louis et al. 2003).

Harmful algal blooms (HABs)

Climate change effects of HABs have been the focus of much scientific research, specifically warming. As a prerequisite for warmer temperatures intensifying a HAB in a given location, the presence of temperatures below those that support maximum growth is necessary as a condition for the HAB to intensify. It has been observed that HABs intensify as water temperatures approach optimal conditions for their growth (Trainer et al. 2020; Gobler 2020). Algal bloom is a serious threat to the sustainability of aquaculture production from an environmental point of view. It has been reported that *flagellates* and *dinoflagellates* taxonomic groups, as well as other harmful species, can be considered potentially toxic and could be responsible for causing stress or even death in finfish and shellfish (Basti et al. 2019; Maulu et al. 2021). There has been some evidence that bivalve mollusks and fish may suffer from the effects of harmful algal blooms, including inflammation, atrophy, and necrosis of several organs of the animals as a result of the effects of harmful algal blooms (Basti et al. 2019; Brown et al. 2020; Rolton et al. 2022).

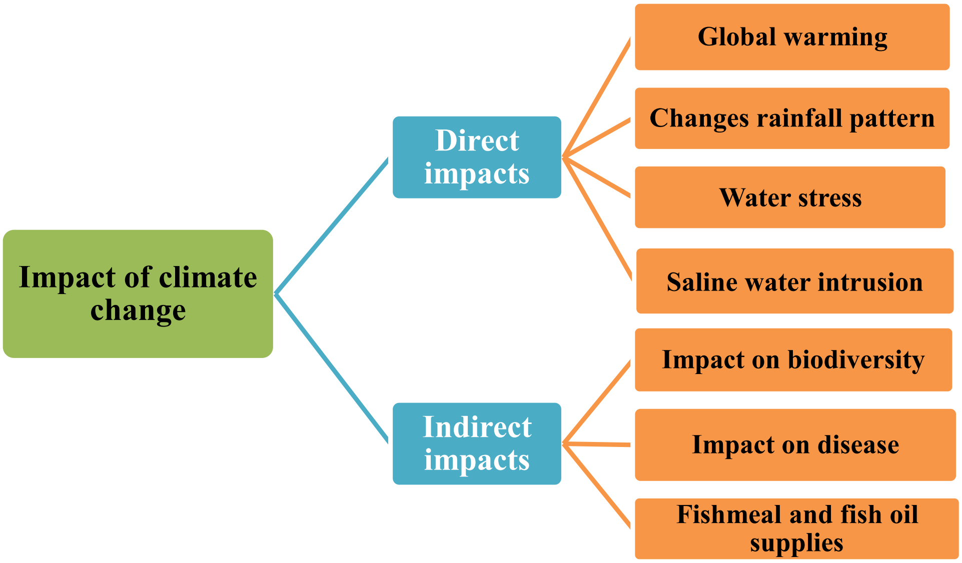
A study published by Halpern et al. (2008) predicts that coastal areas will be the areas most affected by climate change and that many coastal regions are warming much more rapidly than open oceans. Eutrophication is also a risk factor in coastal areas, which is the root cause of many stressors that can occur. It has been shown that excessive nutrient loading and prolonged residence times can promote the growth of a variety of HABs (Glibert and Burkholder 2006). As a result of the large amounts of organic matter present in algal blooms, microbial respiration can be stimulated and produce CO_2, which results in a reduction in dissolved oxygen and increases hypoxia (Breitburg et al. 2018; Griffith and Gobler 2020).

In freshwater, the most obvious example of warming-induced intensification is the HABs caused by cyanobacterial blooms that occur in freshwater, based on several case studies, which indicate that the temperatures that yield maximal growth rates for many cyanobacterial HABs are universally higher than those that yield maximum growth rates for non-harmful eukaryotic algae (Trainer et al. 2020). During the spring diatom blooms within temperate latitudes, surface waters rapidly warm and stratify, eluding incoming water with dissolved oxygen and lower CO_2 concentrations from reaching the bottom waters, thereby promoting simultaneous hypoxia and acidification of the water column(Martin et al. 2011).

Sea level increase and salinity intrusion

In the past few decades, there has been a growing awareness of the vulnerability of many coastal ecosystems, including coral reefs, coastal wetlands such as salt marshes and mangroves, to sea level rise or direct impacts as a result of anthropogenic impacts. In this context, Fig. 2 presents a visual representation of both the direct and indirect impacts of climate change on aquaculture. In response to the effects

Fig. 2 Impacts of climate change on aquaculture



of climate change, freshwater culture techniques are becoming more vulnerable to the rise of sea levels and an increase in salinity intrusions upstream as a result of rising sea levels. Aquaculture infrastructure, including ponds, cages, tanks, and pens, may become inundated by saline water from rising sea levels as a result of sea level rise, especially in lowlands and coastal areas (Kibria et al. 2017). The projected global average sea-level rise between 1990 and 2100 ranges from 20 to 70 cm, accounting for different IPCC greenhouse gas scenarios and climate models (Church et al. 2008). Estuarine zones will be severely impacted by sea level rise, which will lead to saline water intrusion and biotic changes (De Silva and Soto 2009). These will severely impact the coastal habitats including the salt marshes, mangroves, and other habitats that are important for the conservation of wild fish populations and for providing seeds for aquaculture (Kibria et al. 2017).

Previous research indicates that in ecologically sensitive bays characterized by steep topography and human-made structures like sea walls, intertidal habitat is projected to decrease by 13 to 64% over the next century because of the sea level rise (Iwamura et al. 2013). Mudflats and sandy beaches do not migrate inland due to steep topography and anthropogenic structures (such as sea walls) (Galbraith et al. 2002). Because of this, there will be a decline in the breeding success of aquaculture species and the sector’s commercial viability as well. To adapt to changes in the environment, aquaculture producers can move its activities upstream, generate or switch to more salinity-resistant strains of these species, or introduce species that are tolerant to high salinity (Melero-Jiménez et al. 2020; Deb and Haque 2016). There is no doubt that such changes will be expensive and that they will affect the socio-economic status of the communities concerned (De Silva and Soto 2009).

Changes in rainfall pattern

In the past few years, typhoons, hurricanes, and unexpected floods have caused significant economic losses and damage to cage culture systems along rivers and lakes, resulting in the escape of large numbers of finfish (Soto et al. 2019). In a study published by Schewe and Levermann (2012), it is predicted that the increases in temperatures in the late twenty-first century and early twenty-second century will result in frequent changes and shifts in the level of monsoon precipitation down by up to 70% below normal levels. Several parts of Southeast Asia have become prone to excessive monsoon flooding over the past few years, which has become an issue that needs to be resolved (Loo et al.2015).

Climate change brings various adverse effects, such as extreme weather, poor water quality due to plankton blooms, and destructive runoff from floods, leading to structural damage and displacement of aquaculture operations (Park et al. 2010). Floods, classified as natural disasters, occur when water overflows in normally dry areas, impacting production and profits in the aquaculture sector. This phenomenon can be defined as the inundation of an area not ordinarily covered with water, occurring through a temporary rise in the level of a stream, river, lake, or sea (Afia and Iwatt 2023). The increase in sea levels due to global climate change is identified as a contributor to flooding (Go et al. 2018). The repercussions of flooding on aquaculture raise significant concerns, leading to substantial damage and economic losses for both individuals and aquaculture companies. The accumulation of sediment from floodwaters also results in a reduction of water depths (Nayak and Shukla 2023). Flooding disrupts the natural habitats or composition of fish populations in a particular area. As a result, there are changes in the numbers and distributions of various species of fish that are being farmed or cultivated for aquaculture purposes (Rutkayová et al. 2018). Adhikari et al. (2018) observed that farmers encountered increased mortality of Indian major carp (IMC) due to low dissolved oxygen levels during rainfall on hot summer days. Additionally, fish migration from one pond to others during cyclones or heavy floods was noted. Floods also disturb the river's food web, adversely affecting fish populations (Power et al. 2008).

Water stress exhibits significant variation across different regions and, in certain instances, can pose a threat to public health, economic stability, and international trade. Moreover, it has the potential to be a catalyst for conflicts and large-scale migrations. Pressure on states to adopt more creative and sustainable strategies is increasing as global cooperation on water management improves. Water stress or scarcity occurs when there is a lack of safe, usable water in a certain area. Around 70% of freshwater worldwide is used for agriculture, with the remaining 19% going to industry and 11% going to domestic use, which includes drinking (IPCC 2007). On the supply side, sources include surface waters like rivers, lakes, and reservoirs as well as groundwater that can be accessed through aquifers. The amount of water available in important rivers and lakes in Asia and Africa is decreasing regularly (IPCC 2007). Additionally, it has a significant impact on fish, which includes spawning, migration, and the availability of seed for huge farmers. In non-perennial water sources, it may also result in decreased water retention time (Goswami et al. 2006).

Ocean acidification

In addition to temperature changes, an increase in ocean salinity may be an indirect but sensitive indicator of several climate change processes including precipitation, evaporation, river runoff, and ice melt, even though the data are much more limited than that available on temperature changes. There are several factors responsible for ocean acidification, including rising atmospheric CO_2, which is absorbed by the oceans, resulting in low pH levels in the oceans (Doney et al. 2009). In the oceans, CO_2 is exchanged with the atmosphere most frequently. During the past 200 years, since the beginning of industrialization, the oceans have absorbed almost half of the CO_2 emissions from the production of cement and the burning of fossil fuels (Hu 2022). This exemplifies the crucial part that oceans play in the natural processes that cycle carbon globally or the "carbon cycle." In some areas of the global scientific community, such as at the 2004 UNESCO symposium on the Oceans in a High-CO_2 World, this topic is starting to receive significant attention. The chemical reactions that take place when CO_2 is taken in from the atmosphere and dissolved in saltwater are reasonably well understood. On the other hand, little is understood about the biological and chemical mechanisms that underlie ocean life. As a result, anticipating the effects of ocean acidification is a difficult and important task.

Several studies have shown that increasing OA has been associated with a decrease in the calcium carbonate saturation state, resulting in weaker calcified skeletons of some marine organisms and/or a reduction in their net calcification rates (Richards et al. 2015; Whiteley 2011). As a result of ocean acidification, the physiological, organoleptic, and nutritional characteristics of commercial species are likely to be affected (Oliva et al. 2019), as well as consumers' choices (Martin et al. 2019). This acidification problem may also have an impact on macroalgal production (seaweed), but such effects will depend on the kinetics by which different species acquire the inorganic carbon they require (Chung et al. 2017; El-Sayed et al. 2022).

Impacts on biodiversity

The competition for resources and habitat with native species as a consequence of climate change's effects on biodiversity has altered habitats, spread pathogenic organisms, and resulted in genetic interactions through hybridization and introgression (Habibullah et al. 2022; Araguas et al. 2004). Rising temperatures and shifting ocean currents can prompt fish species to relocate to new habitats with preferred environmental conditions, impacting local biodiversity (Perry et al. 2005). Climate change disrupts fish reproductive cycles, altering breeding seasons and spawning behaviors. Warmer waters may accelerate growth rates for some species but hinder growth for others, affecting population dynamics and biodiversity (Munday et al. 2010). Habitat loss diminishes fish breeding, feeding, and nursery areas, resulting in decreased population abundance and diversity (Hughes et al. 2018). Additionally, it is claimed that selective breeding techniques and genetic drift have changed the genetic composition of aquaculture populations, sometimes leading to severe inbreeding (Pauls et al. 2013). Through genetic mutation between the escapees and their wild counterparts, such changes could have an impact on the gene pools of the wild species with their culture counterparts.

Climate change impacts on fish physiology, reproduction, and spawning

Fish reproduction behavior is likely to be affected by variations in temperature, acidification, hypoxia, and pluviosity regimes resulting from global climatic change. Fish, especially those from colder waters like the Atlantic halibut, salmon, and cod, along with intertidal shellfish, are projected to experience increased mortality due to thermal stress caused by the predicted 1.5 °C rise in global temperature in the present century (Hamdan et al. 2012; Gubbins et al. 2013). Therefore, prolonged temperature stress may affect aquaculture productivity in many ways, with a focus on decreasing output. A variety of commercially relevant species may experience changes in their immune systems, cardiorespiratory systems, and aerobic capacity as a result of chronic stress (Brodie et al. 2014; Zhang et al. 2019).

In the long term, climate change affects the physiology, growth patterns, and behavior of aquatic organisms in a way that shrinks the geographic distribution of aquatic life and affects their reproductive abilities (Mitra et al. 2023; Asch et al. 2019). According to Miranda et al. (2013), high temperatures damage the gonads as one of the most detrimental impacts of climate change. During sensitive periods of early development, elevated temperatures can have irreversible effects on fish, affecting larval growth, the prevalence of malformations, and sex differentiation/determination, causing functional masculinization in fish (Yamamoto et al. 2019; Piferrer et al. 2005). In most fishes, climate change is already affecting reproductive and early life history events. To accomplish this, a range of mechanisms are involved at a variety of levels, which are becoming increasingly complex as our understanding of them develops. When in the reproductive cycle thermal challenges occur, the timing of spawning, whether extreme events cause physiological stress, the fish's energy status and reproductive age, as well as their history of thermal exposure and adaptive abilities, are just a few of the many variables that must be taken into account (Pankhurst and Munday 2011).

The process of spawning and successful reproduction is fundamentally governed by evolutionary mechanisms in both freshwater and marine organisms. Organisms have developed to take into account the conditions in their environment, and perhaps the variability of these variables, so they can reproduce and finish their life cycle. This context suggests that climate variability and change can also have a significant influence on the characteristics of spawning and reproduction, as well as on long-term growth and recruitment to adult populations (Fig. 3). Spawning timings and

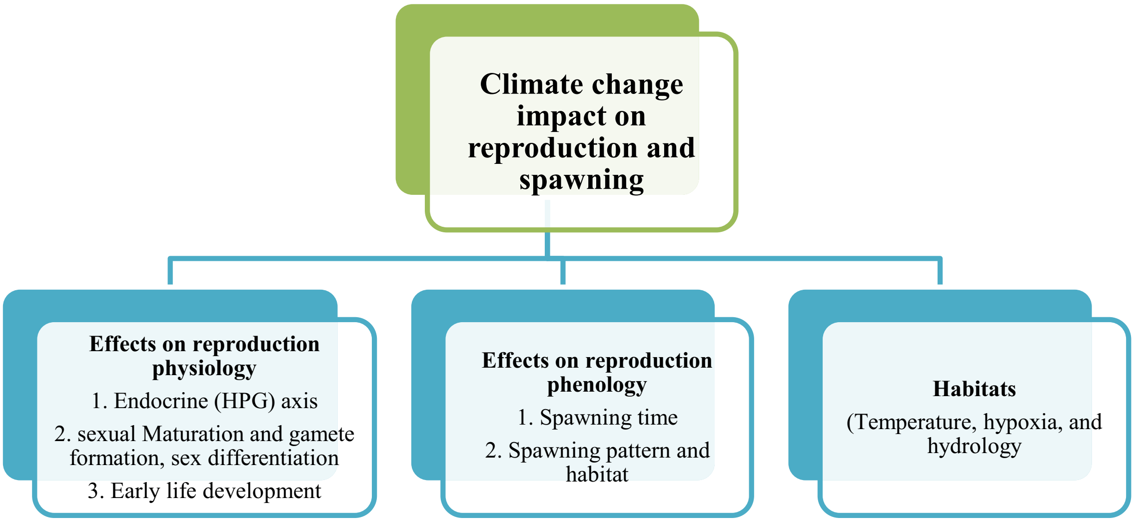


Fig. 3 Effects of climate change on the reproduction of freshwater fish

locations have developed to match the current physical (temperature, salinity, currents) and biological circumstances to increase a larva's chances of surviving to become a reproducing adult or, at the very least, limit the disruption caused by unpredictably climatic events (food). Environmental factors such as temperature significantly influence certain spawning traits, while the type of spawning is determined by evolutionary factors (Jørgensen et al. 2008). During the fish breeding season, watershed rainfall patterns and decreased freshwater flows into estuaries may negatively impact fish recruitment and productivity (Meynecke et al. 2006; Vinagre et al. 2009; James and James 2010). Since fish are aquatic creatures, the continuing changes to aquatic habitats directly influence them. Sexual reproduction, a crucial and energy-intensive process for species survival and evolution in fish, is heavily reliant on the environment to cause or regulate sexual maturation and breeding (Pankhurst and Porter 2003). Environmental factors are also essential for the survival of juvenile fish (Cushing 1969). Due to this direct interference with reproductive processes caused by ongoing, rapid environmental changes, breeding success and survival may be at risk (Servili et al. 2020).

In temperate and cold regions, the majority of fish are seasonal breeders, and the reproductive cycle is predominantly governed by cyclic temperature and/or photoperiod (day length), which controls the timing of spawning to coincide with the ideal conditions for the survival of young (Bromage et al. 2001). Temperature and precipitation in tropical and subtropical areas can start long-lasting reproductive activity. The time and length of the reproductive season, as well as the quantity and quality of reproductive output, can all be affected by unusual temperature regimes (Durant et al. 2007). The lunar stage is a key regulator of reproductive activity in these areas, especially in reef fishes. The fish probably notice the lunar cycle and use it to synchronize several physiological processes, whether on a daily or seasonal basis, such as synchronous gonad development and spawning (Takemura et al. 2004).While a location's photoperiod is unaffected by climate change, many species of mostly marine fish have undertaken poleward migrations as a result of rising temperatures (Vergés et al. 2019). As a result, they are already experiencing substantial changes in photoperiod reproductive periods with potential delays and shorter reproductive seasons.

Implications of climate-driven changes on blue food

Seafood and other aquatic foods, often referred to as "blue foods," are essential for global food security, offering a substantial source of animal protein to meet the needs of a rapidly expanding global population (Willett et al. 2019; Golden et al. 2021; Cao et al. 2023; Atalah and Sanchez-Jerez 2022). They serve as a nutritious protein source, abundant in essential micronutrients, minerals, and fatty acids (Koehn et al. 2022) while generating relatively low environmental pressures (Gephart et al. 2016; Parker et al. 2018) presenting them as an opportunity to promote better nutrition with lower environmental impacts, which are consistent with the sustainable development goals (SDG) for improving nutrition (Goal 2), ensuring sustainable consumption and production (Goal 12), and using marine resources sustainably (Goal 14). In 2020, global blue food production reached an estimated 178 million tons, with aquaculture comprising 49.2% of the total output and supplying over 50% of fish for human consumption (FAO 2022). However, climate change parameters discussed in this paper are anticipated to have significant impacts on blue food. These changes are expected to influence marine ecosystems, potentially disrupting the availability and well-being of key species essential for global fisheries and aquaculture. Recognizing and addressing these impacts is crucial for safeguarding the resilience and productivity of aquatic food systems in the context of on-going climate change. As a result, aquaculture supplies the majority of aquatic foods for the world's population, surpassing the wild harvest from both inland and ocean waters of the planet (FAO 2020). Climate change directly affects blue food (that is, fish, invertebrates, and algae captured or cultured in freshwater and marine ecosystems for food or feed) through rising temperatures, sea-level rise, shifting precipitation patterns, glacier melt-induced freshening, ocean acidification, changes in ocean conditions and productivity, alterations in currents and cycles, increased frequency of extreme weather events, eutrophication, and shifts in the distribution of pathogens, parasites, and invasive species. Rising temperatures decrease dissolved oxygen and increase fish metabolic rates, leading to higher mortality, reduced production, increased feed needs, and greater disease risk (Ruby and Ahilan 2018). A higher CO_2 emission resulting in lower pH impairs the senses of reef fishes and reduces their survival, and might similarly impact commercially targeted fishes that produce most of the seafood eaten by humans (Branch et al. 2013).

Indirectly, climate change can affect aquaculture through its impact on aquafeed supplies. For instance, it may hinder crop production in extreme and increasingly unpredictable conditions, posing a threat to the long-term sustainability of marine products, such as fishmeal (FM) and fish oil (FO) harvesting (Colombo et al. 2023). Harmful algal bloom (HAB) toxins stand out due to their dual impact on both the quantity and quality of blue foods (Cao et al. 2023). Managed aquaculture operations in marine and brackish environments typically face fewer direct impacts from climate-induced changes in ecosystem productivity compared to capture fisheries (Tigchelaar et al. 2021). Food production significantly contributes to environmental change, emitting a 35% of global greenhouse gases (Xu et al. 2021) utilizing half of the ice-free land, and uses 70% global freshwater for agriculture (Poore and Nemecek 2018). Urgent action is required to enhance the sustainability and resilience of aquatic food systems, given the significant climate risk to various outcomes in much of the developing world. Resilience can be achieved by adopting adaptive or transformative strategies that reduce climate hazards, like cutting greenhouse gas emissions, or lessen production system sensitivity, such as cultivating climate-resistant species with lower feed needs (Reid et al. 2019). To promote sustainability, a more balanced diet can be achieved by incorporating fish and other aquatic foods (Gephart et al. 2016; Gephart et al. 2021; Boyd et al. 2022).

Development of climate resilience aquaculture strategies

Sustainable development strategies and decisions can both advance and obstruct sustainable development, much as adaptation and mitigation can advance or obstruct efforts to combat climate change. Figure 4 illustrates the primary strategies for climate resilience in aquaculture. Climate change disruptions can be reduced if adaptation and mitigation are carried out together to reduce the probability of disruption as a result of this change. It should be noted that while these activities may not have adverse consequences from an environmental perspective, they may involve trade-offs between economic and environmental objectives (Denton et al. 2014). Resilience is defined as "a complex system's ability to absorb shocks while maintaining function and reconstruct itself after disturbance." To ensure sustainable, high-yield fish production with minimal environmental impact, it is crucial to adapt to severe climate change, enhancing resilience against its challenges. Solutions aimed at boosting aquaculture productivity sustainably and mitigating climate change effects have been developed. Technology developments have helped aquaculture, like agriculture, adapt to changing climatic conditions. Resilient aquaculture systems can continue to provide ecological, social, and economic advantages even if climate change has a severe impact. Climate-smart aquaculture has been endorsed by many experts around the world as a solution that will increase productivity and provide resilience to ecosystems to lessen vulnerability and is regarded as an important driver of climate change due to the adoption of climate-smart aquaculture (Abisha et al. 2022; Walker et al. 2004).

It has been suggested that most fish producers responded to the existing conditions by diversifying into crops or livestock, diversifying into other businesses/trade, or modifying the time at which first stockings/breeding were first conducted rather than increasing the duration/number of stockings/breeding/units/year in response to the existing circumstances. The listed adaptive strategies can be divided into three categories: private (initiated and implemented by individuals or households in the actor's rational self-interest), autonomous (triggered by changes in the natural, market, or welfare systems of the respondents), and reactive (occurring after the impacts were felt).However, the farmers' inability to point to anticipatory, open-to-the-public, and planned adaptive methods suggests that the farmers' behavior might be viewed as being more independently driven, ad hoc, and non-institutionalized. The majority of fish producers

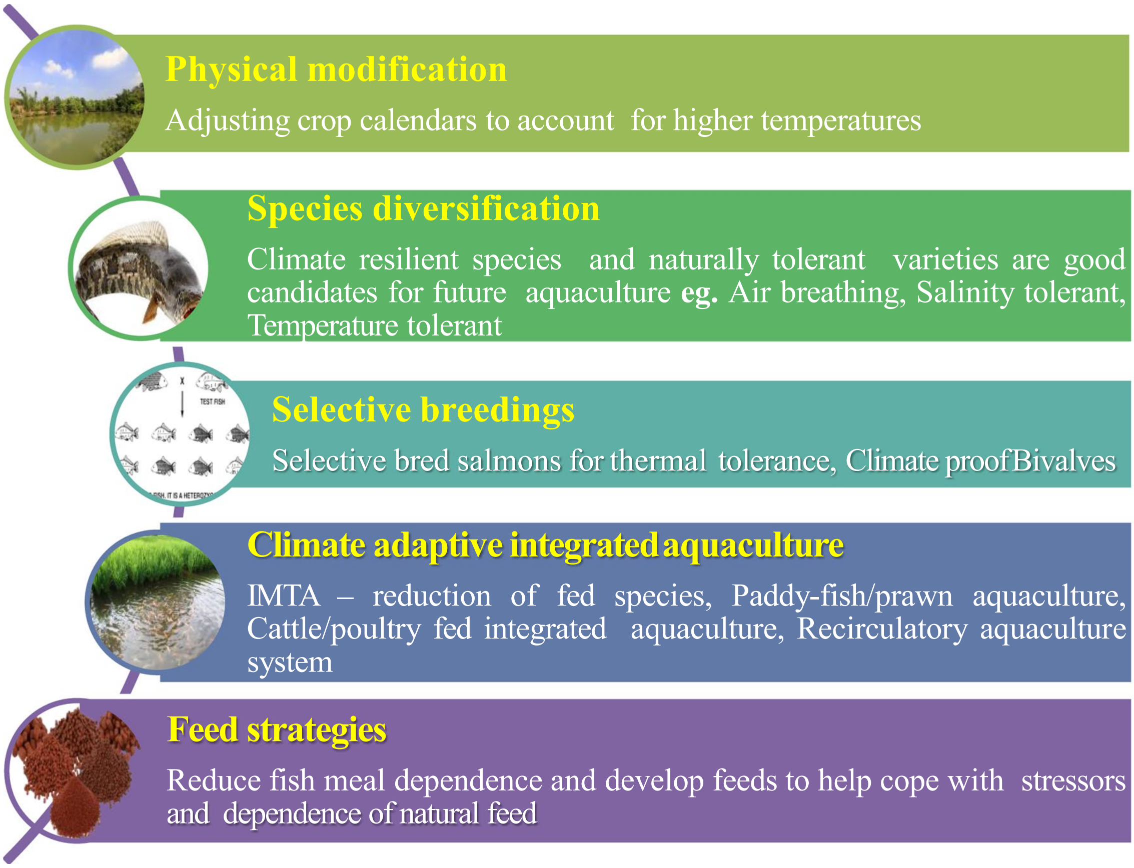


Fig. 4 Development of climate-resilient aquaculture strategies

demonstrated a preference for adjusting stocking or breeding dates rather than reducing the frequency of annual stockings (Dubey et al. 2017a, b). This inclination can be attributed to a perceived adverse impact on their annual income and overall standard of living. Notably, it is commendable that half of the fish producers have proactively diversified their sources of income, engaging in various industries. This strategic move suggests a commendable level of creativity and imagination among the respondents, highlighting their adaptability and resilience in navigating challenges. This diversification aligns with the findings of Dubey et al. (2017a, b), indicating that fish producers are actively seeking innovative changes to their Current Climate Impact (CCI) and underscores the multifaceted nature of adaptive strategies within the fishing community.

Nations have the opportunity to earn credits for their carbon-sequestration initiatives within the domains of forestry, land use, and land use change, as part of their commitments under the Kyoto Protocol—an extension of the United Nations Framework Convention on Climate Change. Activities such as re-vegetation, enhanced forestry or agricultural practices, reforestation (transforming previously wooded land into a forest), and afforestation (converting non-forested areas into forests) are examples of operations that qualify for these credits (Fawzy et al. 2020).

Physical modification

Physical modifications near aquaculture production areas can provide several benefits. Planting shade plants and trees around culture ponds can help mitigate thermal stress by providing shade and reducing direct exposure to sunlight (Bosma et al. 2016). Additionally, shaping the land and constructing higher elevation dykes can help protect against flooding and extreme weather events, enhancing the resilience of aquaculture systems (Velmurugan et al. 2018). These modifications contribute to creating a more conducive environment for aquaculture production while also minimizing the impacts of climate-related stressors. Building ponds on fallow ground for irrigation and fish farming offers a dual benefit by utilizing unused land for both aquaculture and agriculture. By raising the surrounding area, it becomes suitable for vegetable farming, enhancing overall productivity. To prevent fish from being washed away during seasonal floods, bamboo enclosures with trap doors can be strategically placed near houses. These enclosures not only protect the fish but also allow for the introduction of new fish species through floodwater, further enriching the biodiversity of the aquaculture system. This integrated approach maximizes land use efficiency and resilience against natural calamities, promoting sustainable food production. Ponds can be benefited by incorporating nursery areas, which promote the survival of early-life stages of fish by providing optimal conditions for growth and development. Adjusting farming practices to occur either earlier or later in the day helps mitigate the effects of temperature peaks, ensuring that aquaculture operations are conducted during times when temperatures are more favorable for fish health and productivity. These strategies optimize environmental conditions within the aquaculture system, ultimately improving overall performance and resilience in the face of climate change challenges.

The transition from monoculture of *L. vannamei* to polyculture fish is marked by enhanced resilience to illnesses and environmental fluctuations. Polyculture, which involves the co-cultivation of diverse species, diminishes the risk of disease transmission among fish due to their varied dietary preferences (Saithong et al. 2022). This strategic shift enables farmers to mitigate profit loss when *L. vannamei* yields are compromised by adverse environmental conditions. By diversifying their stock through polyculture, farmers reduce their dependency on a single species and enhance their resilience to fluctuations in environmental factors, thereby safeguarding their income. By incorporating *M. rosenbergii* into their cultivation practices, farmers can further bolster their revenue, even in challenging circumstances. Additionally, research indicates that a polyculture system combining L. vannamei and *M. rosenbergii* outperforms monoculture of *L. vannamei* alone, as demonstrated in studies such as that conducted by Chuchird et al. (2009) in Ratchaburi Province. This underscores the economic and productivity benefits of diversifying aquaculture practices.

Species diversification and inland saline aquaculture

Currently, inland saline aquaculture is primarily conducted using saline groundwater as a source of nutrient-rich water. As a result of the salty climate, these environments are not suitable for growing other food-producing crops, particularly agri-crops, even though they could still be used to raise fish. It is important to note that the chemistry of inland saline water is very different from that of coastal saline water. As a newly emerging field of fisheries, the *Penaeus vannamei* aquaculture system is based on inland saline water and has been touted as a magic capsule to boost the overall agri-cum-aquaculture economy of many countries, including India (Pandey et al. 2023). It is becoming increasingly common for farmers in the delta of the Sunderbans to use aquaculture practices such as shrimp and prawn farming, integrated fish-rice farming, and carp polyculture. Climate-resilient aquaculture approaches include the use of wide range of salt-tolerant species (Fig. 5) or species that are a combination of salt-tolerant species, in freshwater settings that are vulnerable to saltwater intrusion. As a result of climate change, species diversification is one of the most important techniques to cope with the effects of the change, which involves using species that breathe air, are salt-tolerant and are temperature-tolerant. Fish capable of air breathing possess a notable advantage, as they can withstand fluctuations

Fig. 5 Species having wide range of salinity tolerance

Salinity Tolerant Species	
	Nile tilapia (*Oreochrombis niloticus*)
	Mozambique tilapia (*Oreochrombis mossambicus*)
	GIFT tilapia
	Spotted snakehead (*Channa punctatus*)
	Grass carp (*Ctenopharyngodon idellus*)
	Silver carp (*Hypophthalmichthys molitrix*)
	Rohu (*Labeo rohita*)
	Giant River Prawn (*Macrobrachium resenbergii*)
	Common carp (*Cyprinus carpio*)

in oxygen levels and temperature changes. The adoption of catfish culture, requiring shallower culture ponds, presents a beneficial response to dwindling water sources in inland saline areas (Abisha et al. 2022). As an alternative to aquaculture, other methods include cultivating salt-tolerant plants and trees along the dykes that will generate income, raising species like *Clarias* spp., *Oreochromis* spp., and *Pangasius sutchi* to provide food, as well as allowing fish to be sheltered by aquatic weeds in culture ponds during hot weather (Abisha et al. 2022; Dubey et al. 2017a, b).

Polyculture approaches can also increase the resilience of farming systems (Dumont et al. 2022). Manipulating combinations of carp species and small indigenous fish enhances fish production in polyculture systems, particularly in southern or South-eastern Asia (Wahab et al. 2011). Mixing species that utilize the same resource at different times or in different areas, thereby avoiding direct competition, can yield similar benefits. Milstein et al. (2006) observed a 50% increase in biomass production and accelerated growth of rohu (*Labeo rohita*) when co-cultured with common carp (*Cyprinus carpio*), a bottom-feeder. Common carp enhance nutrient recycling in the water column by disturbing sediments while feeding on benthic organisms. This sediment disturbance promotes phytoplankton growth, thereby increasing available feed resources for rohu.

Climate adaptive integrated aquaculture

Integrated aquaculture represents a widely adopted approach to integrated resource management, enhancing the efficiency of natural resource utilization. This, in turn, leads to heightened levels of productivity, profitability, and sustainability (Pant et al. 2004; Nhan et al. 2007). To achieve sustainability, integrated aquaculture is a form of sustainable intensification in which a larger amount of food can be produced from the same area of land and water with lesser or no environmental impact.

Integrated multi-trophic aquaculture (IMTA)

Aquaculture, like other human activities, can have negative environmental effects, threatening the long-term sustainability of natural ecosystems (Pillay 2004). Impacts encompass nutrient and chemical pollution, dissemination of pathogens and farmed fish genes, and effects on aquatic ecosystems from capturing wild fish for feed (Weitzman 2019). The discharge of metabolic wastes such as feces, pseudo feces, excreta, and uneaten food from aquaculture facilities is another adverse aspect, resulting in organic and inorganic enrichment of nearby water bodies (Nissar et al. 2023). To address this issue, Integrated Multi-Trophic Aquaculture (IMTA) emerges as a viable solution, designed to utilize the waste generated by fed species to support the culture of extractive species. Since its inception, IMTA has undergone significant evolution, diversifying its components and extending into open waters, thus positioning itself as a promising approach for the future of aquaculture.

In multitrophic aquaculture, a large number of species occupying different trophic levels are integrated and synergistic, which enables them to transfer nutrients and energy through the water from one species to another. As a consequence, the byproducts, such as waste from one aquatic species, are used as inputs to feed another aquatic species (fertilizer, food) (Lal et al. 2023). An ecosystem-based approach to farming fed-fish (finfish), organic extractive species (shellfish), and inorganic extractive species (seaweeds) are part of an integrated farm where different trophic levels are nurtured in a balanced way to ensure the sustainability of the environment. In addition to improving the socio-ecological systems of open oceans, IMTA is also used to reduce water salinity and elevate water temperature to encourage the growth of mussels, shrimp, seaweed, tilapia, and other organisms. Shellfish and seaweed, which are naturally filtering the waste created by the system, could stop further mineralization and temperature rise caused by the waste (Sreejariya et al. 2011). There is no doubt that seaweeds play a central role in IMTA since they can absorb noxious substances, along with impurities, as well as provide cooling to the water (Chung et al. 2017). Figure 6 illustrates the key functionalities of IMTA for climate-resilient aquaculture. The resilience of culture-based fisheries to climate change can be increased with good climate forecasting and climate-smart techniques. Fisheries may also benefit from changes in the environment and productivity that are associated with shifting conditions.

However, the practical implementation of IMTA in open water farming approaches may encounter challenges and obstacles unforeseen during planning. When compared solely with monoculture systems focusing on the most profitable species, IMTA often demonstrates inferior or neutral economic results, primarily because its significant ecological benefits are difficult to quantify. Lance et al. (2017) conducted profit analyses on real cases, examining costs and revenues, and verified that economic performance was the main reason for the recent decline in IMTA development. IMTA implementation also entails drawbacks such as increased requirements for personnel training, expertise development for each species, and integration challenges (Carras et al. 2020).

Recirculating aquaculture systems (RAS)

The concerns and impacts related to the environment, as well as the vulnerability to the effects of climate change and other environmental variables associated with fish production in aquaculture, have led to the implementation of “recirculating

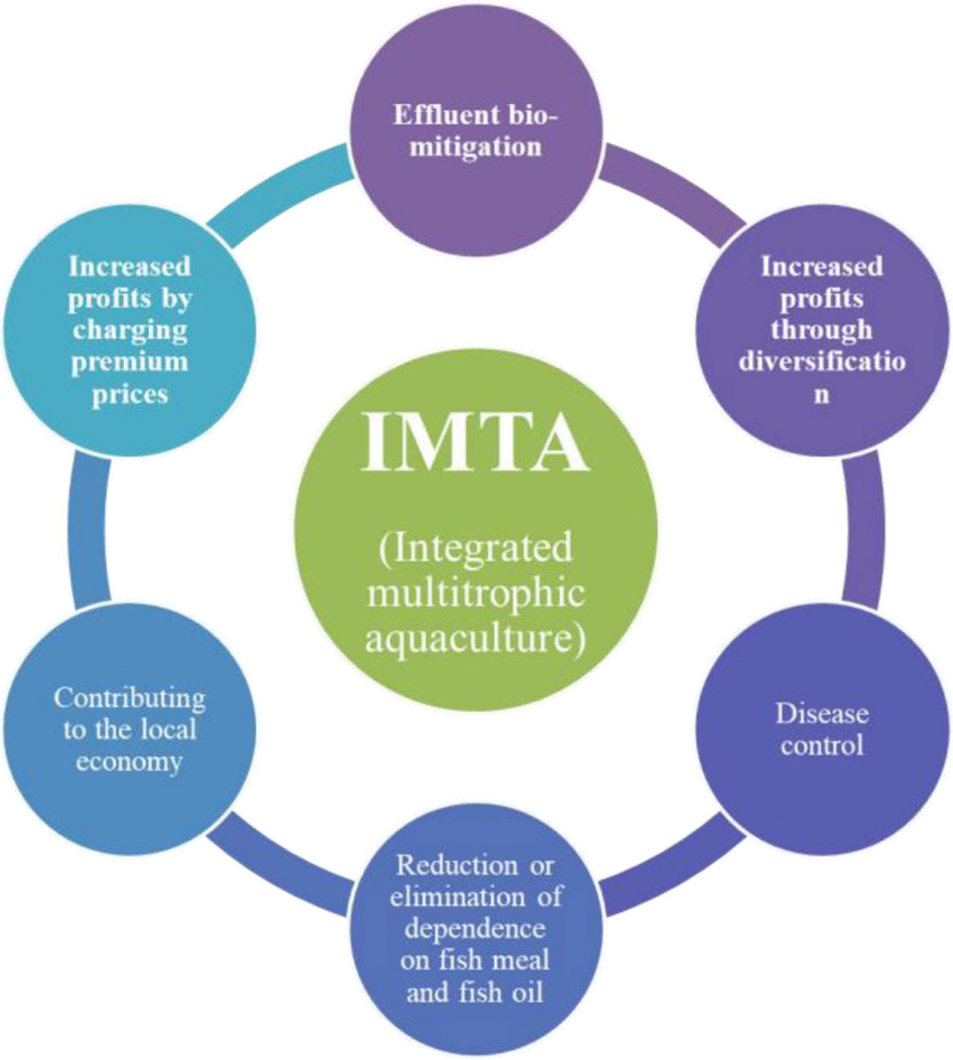


Fig. 6 Functionalities of the IMTA system

aquaculture systems (RAS)" as an adaptation strategy that is becoming increasingly proposed (Ahmed et al. 2019). Aside from being eco-friendly, water efficient, and highly productive intensive farming systems, they also do not adversely affect the environment, such as destroying habitat, polluting water, depleting biotics, negatively affecting biodiversity, spreading diseases and parasites, and destroying the environment (Piedrahita 2003; Bohnes et al. 2022). It has long been known that RAS operates in an indoor controlled environment, which makes them a viable adaptation strategy for the development of climate change shortly. In the context of climatic change, RAS is only minimally affected. These phenomena include variations in rainfall patterns, floods, droughts, global warming, cyclones, salinity fluctuation, ocean acidification, and sea level rise (Ahmed and Turchini 2021). To minimize the direct impacts of the production process on the environment, the RAS allows for the raising of fish in an indoor, indoor, controlled environment that allows for positive interactions between the production process and the environment. A RAS unit comprises a culture tank, solid removal unit, nitrogen removal unit, and disinfection unit. These components recycle water from the culture tanks, reducing water dependency and providing precise control over the culture environment. This adaptability allows RAS to be utilized globally, regardless of climate conditions (Badiola et al. 2018). However, despite its cost-effectiveness, further research is needed in India to determine which species are best suited for RAS implementation.

Aquaponics, which is a form of innovative technology that involves the co-cultivation of freshwater fish with plants using controlled abiotic factors sustainably, could provide a promising tool for mitigating the effects of climate change on reared fish by minimizing the impact of this element on the process (Farrant et al. 2021; David et al. 2022). Efficient nutrient recycling occurs through the transfer of minerals from aquaculture to hydroponics, while water recycling reduces water usage (Haridas et al. 2021). Implementing sustainable systems is essential to protect fish from harmful environmental fluctuations, ensure stable production, and minimize environmental impact. Global food system resilience can be sustained through mixed systems, which provide near-term, local, and regional resilience. Aquaponics offers a sustainable solution by enhancing production, reducing pollution and greenhouse gases, diversifying fish output, improving animal welfare, and mitigating disease risks, while also cutting down on antibiotics, fertilizers, and carbon emissions. It effectively prevents water pollution through waste control (Olesen et al. 2011).

Integrated algae-based aquaculture systems

Algae, as primary producers, are crucial for maintaining the integrity and sustainability of ecosystems (Haridas et al. 2021). Research indicates that integrated algae into aquaculture systems can enhance water quality and increase production yields (Ramli et al. 2020). To reduce CO_2 levels in the atmosphere, algae aquaculture could be a potential solution as well as a source of food and novel compounds for use in biotechnology. As a result, they are aligned strongly with several Sustainable Development Goals (SDGs) that have been set by the United Nations. The use of macroalgae cultivation to capture and sequester carbon through photosynthesis in the deep oceans, sediments, or long-lived products is a promising and priority method of controlling carbon dioxide emissions, with relatively low costs and a high potential for co-benefits on the social and environmental fronts (Fakhraini et al. 2020; Gao and Beardall 2022; Rose and Hemery 2023).

Research indicates that fish ponds play a substantial role in carbon sequestration, primarily due to the accumulation of organic matter in their sediments (Ahmed et al. 2017). The application of fish feed and fertilizers in ponds, aimed at fostering fish growth, contribute to the stimulation of phytoplankton photosynthesis. This process releases organic carbon into the water (Patel et al. 2023). It has also been shown that macrophytes are capable of capturing carbon in ponds as well (Stepien et al. 2016). Additionally, on-farm and/or local production of duckweed (*Wolffia globosa*) and its live consumption have the potential to significantly reduce the carbon footprint of aquaculture. This is achieved by eliminating the energy requirements associated with processing and storage, especially in comparison to the long-distance transport of fish feed. The cultivation of duckweed not only supports the sustainability of aquaculture but also contributes to carbon sequestration efforts (Patel et al. 2023). There is no doubt that wetland ecosystems are one of the most important carbon sinks in soil ecosystems. In fact, because of the high primary productivity of wetland ecosystems and the anaerobic conditions present, wetland soils are capable of efficiently sequestering carbon (Ahmed et al. 2017; Nag et al. 2019). Other than this increasing inputs and/or reducing losses can also help encourage soil carbon storage (Royal Society 2018; Fuss et al. 2018). Nowadays, biochar is widely considered to be one of the most effective ways to sequester carbon dioxide from the atmosphere. In addition to being relatively high in nutrients, biochar produced from algal feedstock may also have the potential to be a good carbon-sequestering material (Yadav et al. 2023).

Adapting nutraceuticals to climate change challenges

Climate change, particularly temperature variations, can disrupt the physiological balance of fish, inducing stress in aquatic animals. Alleviating stress in fish is crucial for optimizing farm productivity, as it is believed to be a key factor in advancing sustainable aquaculture. The application of evidence-based stress management strategies is imperative for ensuring the sustainability and economic success of this industry. The imperative of the moment is to investigate contemporary feed ingredients in combination with nutraceuticals, aiming at immune modulation and stress alleviation in fish. In recent years, addressing this challenge involves employing nutritional interventions for stress mitigation in fish and crustacean. This approach stands out as the most effective and sustainable method for addressing these challenges. It not only allows accurate measurement of physiological changes but also provides significant health benefits to the fish (Mitra et al. 2023). Notably, functional feed additives or nutraceuticals emerge as pivotal contributors to alleviating stress in fish (Fawole and Nazeemashahul 2022). Substantial evidence indicates that nutraceuticals and dietary supplements serve as nutritional modulators of metabolic pathways and immune systems, imparting numerous beneficial effects on well-being. Importantly, these alternatives are environmentally friendly, in stark contrast to antibiotics, with no adverse impact on the environment (Ciji and Akhtar 2021). Research has indicated that nutraceuticals can activate defense systems in fish, even under stressful conditions, thereby potentially mitigating the adverse effects associated with stress to a certain extent (Varghese et al. 2021). Various nutrients, encompassing both micro- and macro-nutrients, including amino acids, fatty acids, carbohydrates (such as β-glucans, peptidoglycans, and chitosan), vitamins, carotenoids, nucleotides, and minerals, have been documented to play a role in the nutritional modulation of immune responses in both fish and higher vertebrates (Herrera et al. 2019). Recent studies propose the inclusion of the sulfur-containing essential amino acid methionine in functional fish feeds as a nutritional strategy to mitigate the stress associated with husbandry conditions and infections (Mir et al. 2017). L-tryptophan has been documented for its ability to alleviate thermal stress in *L. rohita* fingerlings and mitigate both salinity and thermal stress in *L. rohita* juveniles and *Tor putitora* fingerlings (Akhtar et al. 2013). According to

Sharma et al. (2009), supplementation with high protein and vitamin C has been reported to reduce bioaccumulation and alleviate stress issues associated with endosulfan toxicity in *Corydoras punctatus*.

In contemporary practices, there is a growing trend in utilizing phytochemicals, including alkaloids, flavonoids, pigments, phenolics, terpenoids, steroids, and essential oils. These compounds, found in herbs, have demonstrated the capability to strengthen the innate immune system and showcase antimicrobial properties, providing substantial benefits in fish culture. Critically, their application does not raise environmental or hazardous concerns, as highlighted by Chakraborty and Hancz (2011). Phytochemicals have been documented to contribute to various beneficial activities in fish culture, encompassing anti-stress effects, growth promotion, appetite stimulation, tonic and immunostimulatory properties, as well as antimicrobial capabilities (Hoseini et al. 2021; Gabriel et al. 2020).

Conclusion and future prospects

This review has explored the multifaceted impacts of climate change on aquaculture, highlighting the pressing need for sustainable management practices. The evidence highlighted in this review emphasizes aquaculture's susceptibility to climate change, manifested through temperature variations, ocean acidification, and a rising occurrence of extreme weather events. These changes pose significant challenges to aquaculture's productivity, sustainability, and socio-economic value. Furthermore, the review also highlights the effectiveness of climate-resilient adaptation strategies in counteracting these impacts. By embracing innovative practices, technologies, and policies, aquaculture can overcome the challenges of climate change, flourishing to enhance global food security and livelihoods. Continued research is crucial to develop climate-resilient species, breeding techniques, and advanced aquaculture systems. Promoting an integrated approach to aquaculture management is the key for sustainable development. Innovation in feed development to reduce climate-sensitive inputs is essential. Involving local communities in decision-making ensures socially and economically viable adaptation strategies. Community-based management enhances resilience at the grassroots level. Additionally, capacity-building through training on climate-resilient practices is vital.

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Declarations

Conflict of interest The authors declare no competing interests.

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