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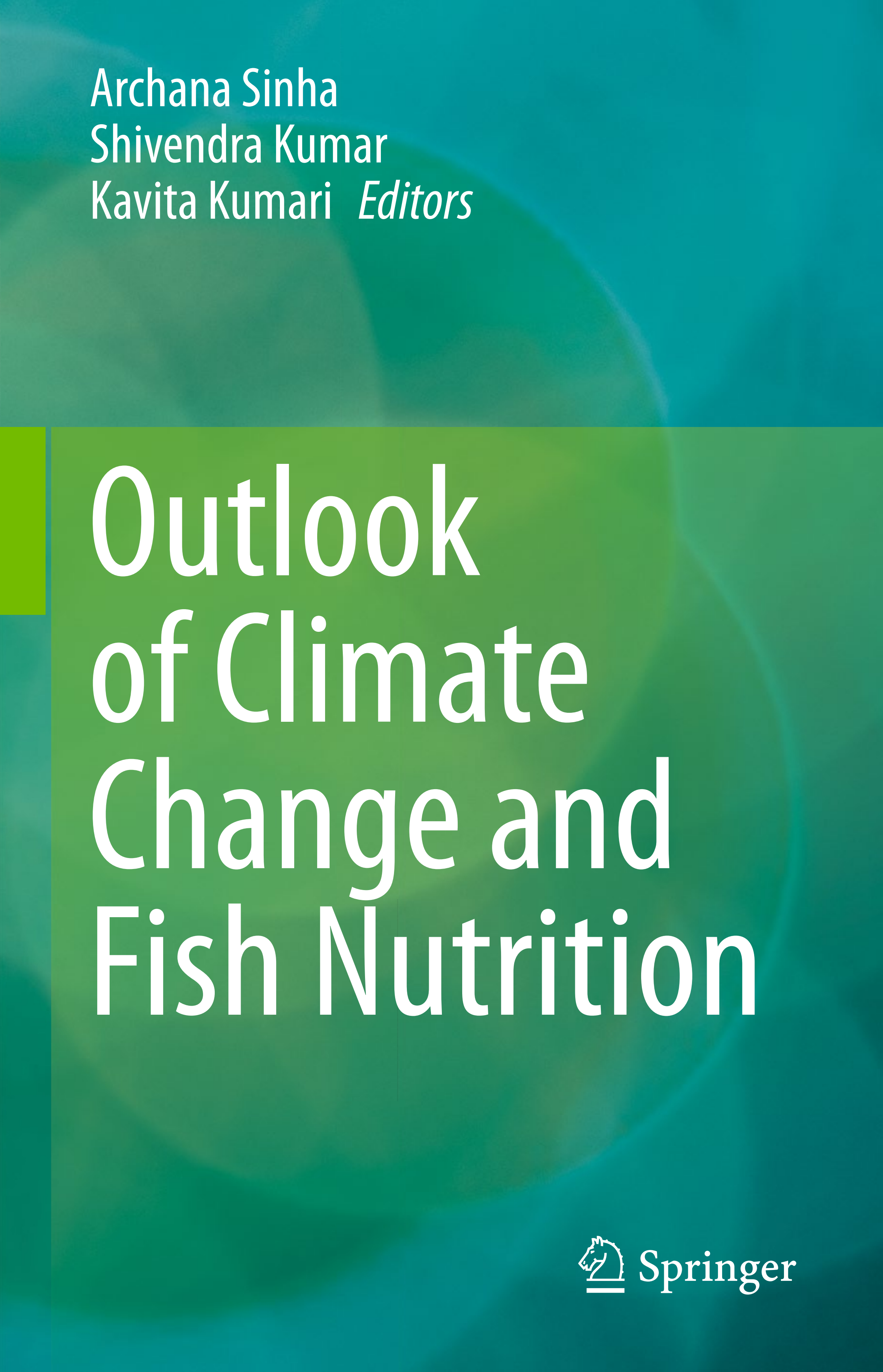
Kavita Kumari *Editors*

Outlook of Climate Change and Fish Nutrition



Springer

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Editors

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Foreword

Climate change has been recognised as the foremost environmental problem of this century, which is now increasingly realised, felt, and assumed a frightful term. It is affecting the available ecosystems on the planet earth, thriving communities, and economies. There is unprecedented growing pressure on the existing food systems including crops, livestock, fisheries, and aquaculture and related livelihoods. Fisheries and aquaculture contribute significantly to food security and livelihoods by providing essential nutrition to three billion people and at least 50% of animal protein and minerals to 400 million people from the poorest countries. Over 500 million people in developing countries depend, directly or indirectly, on fisheries and aquaculture for their livelihoods. Though aquaculture is currently the world's fastest-growing food production system, growing at 7% annually, and fish products are among the most widely traded foods, with more than 37% (by volume) of world production traded internationally, this is equally vulnerable to climate change-mediated impacts.

Recently we have seen a good number of publications including the FAO Technical Paper 627 synthesising current knowledge on climate change impacts, adaptation, and mitigation aimed primarily to cater to the needs of policymakers, fisheries managers, and to a certain extent even practitioners. This document is useful in developing strategies and interventions to minimise, mitigate, and contain climate change impacts by considering various options. It is worth mentioning another publication *Climate Change Impacts on Fisheries and Aquaculture: A Global Analysis* by Wiley-Blackwell devoted exclusively to how climate change is affecting and is likely to affect commercially vital fisheries and aquaculture operations globally based on the experience of several countries.

The book *Outlook of Climate Change and Fish Nutrition* is the outcome of a well-coordinated, concerted, and sincere effort by the editors and a large team of contributors. The entire book is organised into 28 chapters under four parts covering a wide range of fisheries and aquaculture resources under impacts of physical, physiological, social, and economic stressors. The book presents a clear understanding of how changes in the specific ecosystems and individual bioforms and communities respond and adapt and what measures could be taken to ensure that there is minimal effect on growth, reproduction, production, and quality of the products which are vital to supporting food, nutrition, and livelihood security of millions involved in the sector. The chapters and sections are adequately tuned to the courses being taught in fisheries colleges and universities in India, in the region and elsewhere, based on national and regional experience. This book is primarily meant for students, researchers, university teachers, fisheries professionals, and to a certain extent also for practitioners and extension workers.

I wish this book soon on the shelves of institutions and personal collections of individuals.

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Preface

Climate change is projected to impact broadly across ecosystems, societies, and economies, increasing pressure on global livelihoods and food supplies. It is predicted to lead to adverse, irreversible impacts on the earth and the ecosystem as a whole. Although it is difficult to connect specific weather events to climate change, increases in global temperature have been predicted to cause broader changes, including glacial retreat, Arctic shrinkage, and worldwide sea-level rise. Climate change, in particular, rising temperatures, can have both direct and indirect effects on global fish production. Climate change has been implicated in mass mortalities of several aquatic species including plants, fish, corals, and mammals. Being poikilothermic, fishes are very sensitive to any change in the ecosystem.

Though climate change's effect on aquaculture is highly hypothetical, it cannot be overlooked. Fisheries and aquaculture are important sectors of agriculture for livelihood and nutritional security. In commercial aquaculture, it is crucial to ensure that environmental rearing conditions are adequate, if not optimal, for fish growth, welfare, and profitability. Thus, an understanding of how changes in relevant environmental parameters affect growth and physiological performance is vital to the aquaculture production system, and it has become necessary to develop preparedness for the changes and their mitigation strategies through fish nutrition and feeding strategies. This book addresses the potential impact of climate change on the aquaculture sector, specifically related to nutritional and physical-biochemical changes in fishes to adapt to or mitigate the adverse effect of climate change.

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Dholi, India — Shivendra Kumar
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Editors and Contributors

About the Editors

Archana Sinha Principal Scientist (Fish Nutrition), Kolkata Research Station, ICAR-Central Inland Fisheries Research Institute, Kolkata, has more than 30 years of working experience in the field of fisheries and aquaculture. She completed more than 20 research projects, developed technology, served as course teacher for M.F. Sc., Ph.D. and Diploma courses, and guided students for their Ph.D. thesis in the subject Fisheries and Aquaculture. She published more than 100 research papers, 05 books, 20 book chapters, 10 training manuals, etc. and also developed course module on fish nutrition, entrepreneurship development in fish processing, ornamental fish breeding and culture, etc. for ICAR-CIFE and Skill Development Programme of ASCI. She is recognised as an expert by ICAR, New Delhi; NFDB, Hyderabad; MPEDA, Kochi; and NABARD, Mumbai. She organised more than 100 short-term training programmes for unemployed, women, farmers, and entrepreneurs for the development of the fisheries sector. She has been conferred with several fellowships and awards in her field.

Shivendra Kumar Associate Professor, Department of Aquaculture, College of Fisheries, Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar, involved in research, research-based extension and teaching of graduate and post-graduate students. Dr. Kumar pursued M.F.Sc. and Ph.D. in ‘Fish Nutrition and Biochemistry’ from ICAR-CIFE, Mumbai, and postdoc in ‘Fish Nutrition’ at HAKI, Szarvas, Hungary. Major area of his research is in the field of fish nutrition and physiology of temperature regulation including development of strategies to reduce the feed cost. He developed the concept of ‘Nutritional Programming’ for better adaptation to alternative diet in adult fish. Dr. Kumar was awarded the ‘Dr. N. R. Menon best Post Graduate Thesis Award’ by PFGF, India, and ‘Dr. Hiralal Choudhary Young Scientist Award’ by ICAR-CIFE, Mumbai. Dr. Kumar has published 45 research papers in peer-reviewed research journals of national and international repute with 1679 citations, 19 h-index, and 23 i10-index. Besides these he is the author of 5 books, 20 book chapters, and 30 articles.

Kavita Kumari is presently working as a scientist in the Division of Aquatic Environment Biotechnology and Nanotechnology at ICAR-Central Inland Fisheries Research Institute, Barrackpore, Kolkata. She is a Fisheries Graduate. She did her master's in the discipline of Fish Genetics and Biotechnology and Ph.D. in Fish Biotechnology from ICAR-Central Institute of Fisheries Education, Mumbai. Her area of research is application of molecular biology tools for assessment of physiological changes in fish, phylo-geographic variation in fish diversity, and impact of climatic variability on microbes. She was awarded the merit scholarship during her graduation and received fellowship for her postgraduation and Ph.D. work. She also received the young scientist award and gold medal by the Zoological Society of India in the year 2017 and best oral presentation award by Indian Fisheries Outlook-2022. She has many peer-reviewed international publications and delivered presentations in international seminars and symposia.

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Part I

Assessment of Global Warming Impact on Aquatic Resources and Fish Production

The Perspective of Climate Change on the Aquatic Environment and Fish Production

Amit Pande and Pramod Kumar Pandey

Abstract

Climate change, a burning global issue, has had and will continue to impact our environment significantly. Over the years, natural and anthropogenic factors have affected climate leading to alterations in monsoon patterns, North Atlantic Oscillation El Nino/Southern Oscillation, and other changes. In the future, the overall carbon dioxide balance and the foreseen changes are likely to weaken the efficiency of carbon dioxide removal from the atmosphere, disturbing the aquatic environment and ecosystem. Changes in the aquatic environment directly affect the food chain, disturbing the abundance of marine and inland fishes, their recruitment, catch, etc. Global changes in the aquatic environment are likely to change the limits of marine protected areas, and low-lying island countries dependent on coastal economies. Disturbance in the aquatic environment will also affect the propagation of phytoplankton and other algae which could reduce the concentration of atmospheric oxygen. The autotrophic phytoplankton act as carbon dioxide sinks and account for nearly half of the total global photosynthesis. Their absence would have severe consequences as the aquatic food chain would get cracked. Looking at this foreseen situation faced by humans the chapter is attempted to present some insights due to climate change with severe consequences for the aquatic environment and fish production.

Keywords

Aquatic environment · Climate change · Fish production

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1 Introduction

Climate change refers to a persistent alteration of temperature and distinct weather patterns in a specific location or the planet as a whole. Climate, often confused with the weather, includes weather conditions exclusively averaged over a few decades for a particular place. On the other hand, the weather has temperature, atmospheric pressure, wind, humidity, precipitation, and cloud cover during the day. In simple words, the weather is a term that expresses the degree to which it may be cold or hot, high or low, gusty or calm, dry or muggy, rainy or snowy, with a clear or obscure sky.

Climate change, the consequence of burning fossil fuels, for example, oil, gas, and coal, is having a catastrophic effect on our environment. When burnt, the fossil fuels liberate carbon dioxide into the air, subsequently heating the earth. Climate change has not spared any form of life on earth, be it aquatic or terrestrial. According to the Intergovernmental Panel on Climate Change (IPCC), climate change can contribute to the global rise in sea level up to 1 m (Rahmstorf 2010) if greenhouse gas emissions keep escalating. Precision satellite altimeter data of 25-year time series suggests that the global mean sea level could rise 65 ± 12 cm by 2100 compared to 2005. This report is quite close to the one from IPCC's fifth Assessment Report (AR5) model projections (Nerem et al. 2018). There has been an upsurge in the pieces of evidence supporting rapid climate change. It is predicted that by the year 2100, the global temperatures will increase by 4 °C, with notable differences in precipitation patterns. Thus, in this situation, assessing the costs of biodiversity and its mitigation remains a daunting task for ecologists (Thuiller 2007).

Assimilation of incoming solar energy and reflected radiant energy are the consequences of greenhouse gases, for example, carbon dioxide, methane, etc. Changes in the concentrations of greenhouse and other atmospheric gases disturb the global radiation budget (Gribbin 1988), which results in an escalation of atmospheric temperature. A rise in atmospheric temperature by a few degrees can cause hydrologic changes that can disturb water's physical and chemical properties. Further, minor temperature changes can have a significant influence on climate (Roessig et al. 2004), leading to changes in the aquatic environment with alterations in aquatic life, namely fish, invertebrates, and plant species of marine and estuarine ecosystems (Kitaysky and Golubova 2000; Stevenson et al. 2002). Thus, with a relatively small temperature rise, there is a change in distribution and shifts in marine and inland fishes (Perry et al. 2005; reviewed by Myers et al. 2017).

With the expansion of industrialization, different detrimental compounds are being introduced into the atmosphere, resulting in intense environmental alterations. These environmental alterations have enabled the retention of radiant energy, ensuing in elevated atmospheric temperature that impacts climate. These climatic changes influence ecosystems, communities, and population structures (Walther et al. 2002). A scale of such changes has been observed in aquatic and terrestrial systems (Root et al. 2003; Parmesan and Yohe 2003; Perry et al. 2005). Other issues affected by global climate change include alteration in boundaries of marine protected areas and low-lying island countries dependent on coastal economies and diseases (Perry et al. 2005).

Carbon dioxide (CO_2), a greenhouse gas that accounts for climate change, is highly soluble in water. It results in the accumulation of more bicarbonate as a consequence of increased levels of atmospheric CO_2. Enhanced water temperatures, and acidification of aquatic water bodies, including oceans, have severely affected the aquatic environment (Roessig et al. 2004; Nikinmaa 2013) and even involved the distribution shifts in marine fishes (Perry et al. 2005). As a consequence of a rise in sea temperature, it is known that the distribution of exploited and non-exploited fish was affected as nearly two-thirds of species shifted in mean latitude or depth or both over 25 years (Perry et al. 2005). Alterations in inland aquatic ecosystems through a change in water quality and other pathways have also been predicted (Nikinmaa 2013; Chen et al. 2016). Expected climate change in the future is likely to harm inland as well as marine aquatic ecosystems through different pathways, along with alterations in water quality (Kitaysky and Golubova 2000; Winslow et al. 2003; Paukert et al. 2017). Thus, devastating effects can be well predicted for the aquatic ecosystems as the nature of interaction among different aquatic organisms can be altered due to an increase in water temperature and other factors (Roessig et al. 2004; Myers et al. 2017; Timoner et al. 2021; Whitfield 2021).

2 Factors Responsible for Climate Change

Several factors bring about climate change. Increased sea levels, construction of dams, scarcity of food, temperature variations, gaseous emissions, and increased rate of evaporation are some crucial factors responsible for climate change that is known to cause alteration in an aquatic environment. It is predicted that climate change would accelerate the melting of glaciers. The thermal expansion of seawater will raise the sea level by nearly half a meter by 2100, disturbing life in aquatic ecosystems to a great extent. This would seriously affect aquatic organisms as their existence may be threatened or extinct by the end of the century (Williamson and Guinder 2021). Manmade dams can alter the local climatic conditions and are already harming ecological niches by disturbing the native biodiversity, including the migration patterns and breeding of aquatic organisms (Null et al. 2013; Kirkland et al. 2021; O’Mara et al. 2021).

2.1 Water Regulation and Manmade Dams

It has been demonstrated that the Coldwater habitat for fish species has been reduced by water regulation, construction of dams, and land-use change with a variation in stream temperatures. Climate change has consequences on hydroclimatic conditions and impacts water temperatures downstream of the dams, affecting ecology as stream temperatures are sensitive to fluctuations. Thus, reservoir regulation affects stream temperatures and Coldwater habitat with climate change (Null et al. 2013). A recent study conducted at 30 dam sites across various environmental settings throughout Massachusetts (USA) has shown that most dams warmed temperatures downstream with variable magnitudes. It was observed that cool headwater streams having wide impoundments faced maximum warming. It was intriguing to note that 75% of the cold/cool water sites shifted to warmer thermal classes downstream, with the thermal effects of dams being most significant during the lower flow periods (Zaidel et al. 2021). A similar phenomenon has been predicted for Indian Coldwater fishes, as a variation in the pattern of the reproductive biology of golden mahseer from the lesser Himalayan region concerning regional climate change had consequences on breeding phenology (Joshi et al. 2018).

2.2 Climate Change and Air Quality

Deforestation, considered responsible for climate change, seriously affects the quality of air that we breath. An essential but usually ignored carbon dioxide consumer group is the autotrophic phytoplankton that acts as carbon dioxide sinks. Moreover, the autotrophic phytoplankton accounts for nearly half of global photosynthesis. However, terrestrial plants have always gathered attention (Falkowski 2012). Alteration in an abundance of phytoplankton will affect the overall carbon dioxide balance via the oceanic carbon cycle. The foreseen changes would diminish carbon dioxide removal from the atmosphere (Cermeno et al. 2008). Notably, there has been a global decrease in oceanic phytoplankton (Boyce et al. 2010) which is alarming.

2.3 Ocean Acidification

Ocean acidification, a result of rising atmospheric carbon dioxide (CO_2), is a consequence of burning human fossil fuels. Atmospheric CO_2 reduces ocean pH and causes a comprehensive shift in carbonate content, thereby altering the water chemistry. The process of ocean acidification is well documented, and it is predicted that the rate will accelerate over this century if forthcoming CO_2 emissions are not curbed. As a result of acidification, chemical speciation and biogeochemical cycles of many elements and compounds in the seawater can be altered (Doney et al. 2009). One of the consequences of acidification is the reduced calcium carbonate saturation states, which influences shell formation in marine organisms from plankton to benthic molluscs, echinoderms, and corals. However, ocean acidification may increase carbon fixation rates in some photosynthetic organisms (reviewed by Doney et al. 2009).

2.4 Solar Forcing

Solar forcing or the changes in solar radiation in a climate model is also known to affect the aquatic environment. Solar forcing can shift towards the Arctic Oscillation/ North Atlantic Oscillation during periods of reduced solar forcing. Reduction in solar irradiance leads to colder temperatures over the continents in the Northern Hemisphere, especially during winter (1–2 °C), a fact that is in agreement with historical records and proxy data for surface temperatures (Shindell et al. 2001). It is predicted that by 2100, global ocean temperatures will increase by 1–4 °C. The increased temperatures will affect the stress physiology of fish as they are most vulnerable to global warming (Alfonso et al. 2021). The enhanced temperature may alter the capacity of fishes to cope with other stressors, compromising their fitness. In addition, rapid temperature increases are known to induce acute stress responses in fishes and might be of ecological relevance in particular situations. Fishes exposed to high temperatures cause stress that triggers the release of catecholamines and cortisol. Elevated cortisol responses due to an acute rise in temperature have been reported in several fishes, with a few exceptions (reviewed by Alfonso et al. 2021).

2.5 Anthropogenic and Natural Causes

Anthropogenic activities like the expansion of cities, industrialization, deforestation, burning of wood, and agricultural activities contribute to greenhouse gases. For instance, livestock produces methane during enteric fermentation, while an enormous amount of nitrous oxide is generated during the manufacture of chemical fertilizers. Anthropogenic interventions have led to the increase in greenhouse gases, namely carbon dioxide, methane, nitrous oxide, and halogenated compounds, for example, CFCs and SF6 are significant contributors that accumulate in the atmosphere and trap the sun’s heat reflected from the earth leading to the phenomenon of the greenhouse effect (Wallington et al. 2009; Kweku et al. 2017).

Several studies on historical records on climate change show that anthropogenic and natural causes affected global greenhouse warming over the twentieth century, with an accelerated upsurge in aerosol sulfate emissions which started around 1950 (Crowley 2000; Jones and Mann 2004; Stern and Kaufmann 2014; Hegerl et al. 2019). Based on modeling and attribution studies, it is known that aerosol forcing influences regional temperatures, leading to continuing alterations in monsoon patterns besides Atlantic variability. These historical changes in atmospheric conditions are said to be responsible for long-term climate variability. For example, the North Atlantic Oscillation (Hegerl et al. 2019) is known to disturb wind speed and direction, besides alterations in air temperature and rainfall. North Atlantic Oscillation is known to affect fishery resources and fishery yields by aggravating the abundance of target species, their recruitment, catchability, and body condition with cumulative and synergistic action (Báez et al. 2021). Some of the consequences that can be foreseen include distribution and shifts in marine and inland fishes (Perry et al. 2005).

2.6 Temperature

In Black Sea trout (*Salmo trutta* labrax Pallas, 1814), an acute increase in temperature can trigger secondary stress responses marked by elevated glucose and lactate levels because of critical thermal challenges. Temperature fluctuations may also alter blood osmolality besides hematological variables. Besides having an inhibitory effect on the fish immune system, acute thermal stress can also affect total protein and serum ion concentrations. It has been observed that short-term acute thermal exposure can also result in serum ionic imbalance in trout, with the restoration of homeostasis (Bard and Kieffer 2019; Dengiz Balta et al. 2017). Further, thermal stress can alter the levels of heat shock protein (HSPs) at the cellular level by affecting the endocrine stress system. For instance, in red blood cells of rainbow trout *Oncorhynchus mykiss* (Walbaum 1792), the adrenergic system can enhance the response of HSP, while cortisol inhibited heat stress-induced levels of HSPs (reviewed in Alfonso et al. 2021). Chronic exposure to elevated temperature can lead to severe consequences for the resting stress physiology of fish because of alteration in the brain's noradrenergic and dopaminergic systems. Moreover, a warmer climate can also alter the stress-coping capacities of fish.

3 Climate Change and Aquatic Environment

The quality of water in an aquatic environment can have a remarkable change in the aquatic habitat. Gaseous emissions in the form of CO_2, SO_2, and oxides of nitrogen (NOX) can alter the precipitation chemistry of water. An increase in the concentration of SO_2 results in more sulfate ions that enter water bodies, reducing their pH. Acidification and increased water temperatures directly affect dissolved organic carbon (Evans et al. 2005). It is known that pH and dissolved organic carbon impact the bioavailability of mercury at the bottom of the aquatic food chain (Adams et al. 2009; Dittman and Driscoll 2009). Bioaccumulated mercury in aquatic food chains can attain maximum concentrations in edible tissues of fish living in freshwater and marine environments. Mercury absorbed from the diet gets distributed to all the tissues in the body. Thus, consuming such fish can introduce mercury in humans, which can easily cross the blood-brain and placental barriers resulting in several neurological manifestations (Fitzgerald and Lamborg 2014; Clarkson 1993; Amap/UNEP 2015).

Alteration in precipitation patterns and increased air temperature can change stream and river discharge patterns (Clow 2010; Leppi et al. 2012). Rising air temperatures in ice- or snow-covered regions will speed up snow melting, alter the hydrological system by increasing nearby streams' flow, and create a water deficit late in the season. These late-season shortages leave less water in the channel to be warmed during the hottest months of the year. Though concentrations of chemicals are likely to be diluted during high flows, the total pollutant load may increase (Grigas et al. 2015). Chemical concentrations and water temperatures will increase during low flows, but the whole load may also decrease. For instance, in the

Mississippi River Basin, runoff of agricultural nutrients (e.g., nitrogen and phosphorus) and sediment would have relatively higher concentrations but low total loads. In some extreme conditions, high flow can cause high concentrations of these agricultural pollutants (Reba et al. 2013). A similar flow of chemical concentration/load pattern has been witnessed in urbanized watersheds (e.g., Grigas et al. 2015).

Similarly, rock weathering and solute transport components are influenced either directly or indirectly by the local climate. Local hydrology, directly linked to the environment, governs the subsurface flow of oxygen and water and the surface and subsurface transport of weathering products. Further, both temperature and hydrology strongly influence watershed geochemical reaction rates and, as such, define the resultant water chemistry in waterbodies draining those watersheds. Significant changes in climatic conditions, such as thermal and hydrological regimes within mineralized areas, can change watershed chemistry (Rogora et al. 2003).

Several studies have documented increases in rock weathering solutes (e.g., dissolved sulfate) over the last several decades attributed to increases in climatic warming (Mast et al. 2011). A recent study has documented that increased concentrations of dissolved metals are known to be the products of pyrite weathering that are toxic to freshwater fishes (e.g., Zn, Cu, Cd; Todd et al. 2012). This study concluded that upsurges in concentrations of instream toxic metal were likely attributable to several climate-influenced factors, including increased rock weathering, new subsurface flow, weathering pathways resulting from loss of frozen surface ground, and a decreasing groundwater table (Todd et al. 2012). Notably, if water chemistry changes, the downstream water quality worsens and may increase toxicity thresholds that directly affect fisheries.

Global climate change is also predicted to change air temperature, precipitation, and emissions of CO_2, SO_2, and NOX. Other effect leads to increased water temperatures, reduced dissolved oxygen concentration, altered water chemistry, and chemical load. One of the costs of climate change is the geographically atypical warming of oceans. Changes in temperature and salinity due to global warming can mutually reduce the density of the ocean surface, intensify vertical stratification, and alter surface mixing. Moreover, evidence suggests that inland waters are warming, as well as influencing river runoff. An increase in vertical stratification and water column stability in the oceans and lakes can reduce accessibility to nutrients in the euphotic zones affecting primary and secondary production (Barange and Perry 2009).

Climate change has also been associated with upwelling. Upwelling is a phenomenon in which deep coldwater rises towards the surface. Winds that blow across the ocean surface push the water away, resulting in the rising of underneath water to the surface thus, replacing the water moved away. Climate change can alter upwelling, as evidence shows that the seasonality of upwelling may be affected due to climate change. However, to understand coastal upwelling, the present climate models are inadequately developed and require refinement to predict rising sea levels. Rising sea levels will remain a severe concern for low-lying coastal areas, for example, small-island regions, coastal Americas of the Atlantic and Gulf of Mexico, the Mediterranean, the Baltic, and Asian mega deltas (Barange and Perry 2009).

It is well known that the phenomenon of ocean acidification has been reducing the pH of the water in the marine environment. It is predicted that a further reduction in pH will have severe consequences for shell-bearing organisms, tropical coral reefs, and coldwater corals. Climate change will affect inland ecosystems resulting in altered land use, including variations in sediment loads, water flows, and physico-chemical changes. These changes will impact community composition, production, and seasonality in plankton and fish populations, putting additional pressure on inland fish production (Barange and Perry 2009).

4 Climate Change and Plankton

Planktons are tiny organisms that can affect climate in several ways. They absorb and scatter light, warm the ocean's top layers, and produce volatile organic compounds, such as dimethyl sulfide, which supports the formation of clouds. Planktons play an essential role in moving carbon around the oceans, on a scale large enough to affect carbon dioxide levels in the atmosphere (Falkowski 1994).

It can be foreseen that the climate will get warmer in the next century due to an increase in greenhouse gases, and so will the oceans. Warm climatic conditions would deplete oxygen in the water and result in a reduction of phytoplankton. Since 1950, there has been a spectacular reduction in phytoplankton due to the gradual warming of the oceans. It is known that phytoplankton thrives better in cooler waters. Therefore, they migrate to cooler areas of the sea when other parts turn too warm. Oceanographers have tracked environmental changes like temperature and salinity to estimate the migration of phytoplankton over the next century. It is predicted that phytoplankton along the North Atlantic coast will migrate towards cooler waters off the coast of Greenland, reducing the source of food for fish and other aquatic organisms.

Phytoplanktons play an integral role in moderating the earth's climate as they absorb CO_2 emissions. Phytoplanktons absorb CO_2 as plants do, and when dead, they sink to the bottom of the ocean, locking the carbon for several millennia. Phytoplankton account for half of the global photosynthesis preventing global warming to a great extent (Huertas et al. 2011).

Significant and globally consistent shifts have been detected in species phenology, range extension, and community composition in marine ecosystems (Beaugrand et al. 2003). The shift in plankton communities towards the poles indicates ocean warming and its impact on marine ecosystems. Global shifts in zooplankton populations can affect marine life that feeds on plankton, especially fish (Jonkers et al. 2019). On comparing pre-industrial and modern-day zooplankton samples, it has been assessed that the average community had shifted 602 km towards the poles from the pre-industrial era to date. However, the degree of displacement ranged from 45 to 2557 km, depending on the degree of change in sea surface temperature. In the northern hemisphere, it was found that plankton communities had shifted northwards in response to ocean warming. Some species that feed on zooplankton would migrate to cooler waters, while others may not do so and thus eventually perish.

5 Climate Change and Benthic Community

Information about benthic variability about climate change and other effects is meagerly available. Efforts are on to unravel more evidence from time-series observations. Climate change may modify population dynamics over time and space, phenology, and geographical distribution of communities and species (Dulvy et al. 2008; Birchenough et al. 2011). Under such conditions, several species would lose their habitat and become extinct in the aftermath of biogeochemical changes, ecosystem functioning, and biodiversity. Habitat loss and extinction can be expected over time, with aftermaths of biogeochemical changes, ecosystem functioning, and biodiversity.

6 Climate Change and Fish Production

Several effects of climate change have been observed on the ecosystem and fish production. In recent decades, the global primary production of the oceans has shown a trivial decrease. In contrast, a slight upsurge in global primary production is expected over this century, however, with enormous regional differences (Barange and Perry 2009). There would be reduced ice cover, warmer-water temperatures, longer seasons due to increased algal abundance, and productivity in high-latitude/altitude lakes (Mcclanahan and Cinner 2012). However, diminished algal mass and reduction in productivity are also predicted primarily due to the reduced resupply of nutrients in some deep tropical lakes. It is expected that the intensification of hydrological cycles may substantially influence the limnological progressions. It would affect the productivity of all forms of aquatic life because of augmented runoff, discharge rates, flooding areas, and water levels during the dry season (Mcclanahan and Cinner 2012).

Climate change is said to direct most terrestrial and marine species near the poles, intensifying the propagation of warmer-water species and shrinking the ones in colder water. The most rapid switches are projected to occur in fish communities in the oceans, including those that would migrate in response to surface warming, resulting in a surge in abundance towards the poles. In contrast, a decline in populations near the equator will be inevitable.

An increase in temperature and light intensification would result in differential responses between plankton components suggesting an alteration in the environment of marine and freshwater fishes due to predator-prey mismatch (Barange and Perry 2009). Although there is a limited conformation supporting upsurge in outbreaks of disease related to global warming, however, dissemination of pathogens to higher latitudes has been observed, which might lead to some emerging diseases.

In a rapid timescale, i.e., within a few years, rising temperatures will negatively impact fish physiology resulting in considerable limitations for aquaculture, and alteration in the distribution of species, besides possible changes in abundance as recruitment processes will be afflicted. The timings of important events like life history would diminish, particularly affecting short-lived species like plankton, squid, and small pelagic fishes. During intermediate time scales ranging from a few years to a decade, the recruitment success would be altered due to temperature-mediated physiological stresses and changes in phenology impacting the abundances of several marine and inland fish populations. However, the predicted impacts at multi-decadal or long-time scales would depend upon changes in net primary production in the oceans and their transfer to higher trophic levels (Barange and Perry 2009). A global model has been predicted for the 2050s considering different life stages, timeframes, and dispersal scenarios to unravel the thermal performances of *Salmo trutta* and *Salmo salar*. It has been demonstrated that thermal performances of varying life stages would fluctuate for specific periods. The thermal performances and model predictions suggest declines in habitat area and poleward shifts. The fish would disperse to find suitable habitats to mitigate the warming effects. However, dams may restrict their movement to sites linked to high performance (Kärcher et al. 2021). Similarly, concerns have been raised about the Atlantic salmon, which faces the challenges of reduced marine survival in a rapidly changing environment, as a consequence of climate change (Thorstad et al. 2021).

7 Impact on Inland Ecosystem

Climate change is causing alteration in the composition of species assemblages, abundance, biomass and distribution, fish yields, and the efficiency of fishing methods and gears. Inland fisheries have a significant contribution to meeting the food and livelihood demands of the fishing community. Unfortunately, diverse anthropogenic interventions have resulted in climate change affecting both fish and fishing communities. Injudicious use of water, overfishing, the introduction of exotic species, pollution, habitat degradation, and the rising human population have dented inland fisheries globally. Therefore, climate change will lead to changes in freshwater habitats and the fish assemblages they support. However, a few of these effects may benefit inland fisheries, especially those based on native fish populations (Harrod et al. 2019).

Freshwater ecosystems have a reasonably low buffering capacity and are relatively sensitive to climate-related variability. There can be a range of physiological and ecological impacts on fish and freshwater ecosystems supporting inland fisheries related to water temperature, water availability and flow, and other environmental disturbances. Climate change is expected to impact inland fisheries due to cumulative deviations in water temperature, nutrient levels, and precipitation patterns. For example, in the Ganga River system, most fish breed during the monsoon because of their dependence on seasonal floods. During the breeding months, a fall in precipitation may alter the required flow of turbidity essential for breeding the Indian major carp (IMC). A shift in rainfall pattern during the breeding season is responsible for the difficulties encountered in breeding and consequent recruitment of the IMCs juveniles in the river.

Impacts of direct and indirect climate change may lead to considerable shifts in species compositions. However, overall productivity may be sustained due to the high diversity and resilience of tropical systems and several invasive fish species. Climate change has continued to have a marked global impact on freshwater ecosystems, fish, and other aquatic taxa, besides providing goods and services, including fisheries (Myers et al. 2017). Almost all biological and chemical processes in freshwater ecosystems are influenced by temperature. Critical chemical transformations, dissolved oxygen concentrations, degradation, evaporation, the rate of biochemical processes within the aquatic organisms, disease risk, parasite transmissions, and the trophic interactions between consumers and their prey are some effects that are influenced by temperature (Miller et al. 2014). There would be harmful effects at longer time scales on Coldwater fish species compared with the ones inhabiting the warm water, which would be advantageous. The predicted response for cool water species would be beneficial in the northern parts but negatively affected in the southern parts of their range (reviewed by Barange and Perry 2009).

8 Impact on Marine Ecosystem

Climate change will have a marked effect on important marine organisms such as zooplankton constituting the base of the marine food chain, and calciferous organisms like shrimps, oysters, corals, and others. A rise in sea temperature is a significant reason for coral bleaching and reef ecosystem damage (Barange and Perry 2009). In 1997–1998 there was a mass bleaching event of corals worldwide with massive mortality, which overlapped with a large El Nino event, instantly switching over to a strong La Nina. Catastrophic bleaching with colossal mortality of about 95% was recorded from shallow and sometimes deep-water corals (Wilkinson 1998). It is predicted that carbon dioxide, a contributing factor to ocean acidification, could impair several ecosystems due to the elimination of several coral reefs. Mangroves and salt marshes are essential for maintaining wild fish stocks, and the source of seed for aquaculture would be lost. The marine food web may disrupt the food chain in the transformed marine ecosystem, eventually affecting marine fisheries and hamper distribution, productivity, and species composition of global fish production. The complex and interrelated impacts on oceans, estuaries, and seagrass beds provide habitats and nursery areas for fish that can shrink and eventually be lost. It is estimated that by 2100, the global fish catch from the oceans is expected to decline dramatically in global biomass and catches over the twenty-first century.

Diverse models predicting the effect of climate change suggest that by 2050 the potential of global fish catch may fluctuate by less than 10% depending on the trajectory of greenhouse gas emissions with significant geographical variability. It is predicted that reductions in marine and terrestrial production in almost 85% of coastal countries are anticipated with a wide variation in their nationwide adaptability. The distribution of zooplankton has transformed due to climate change, leading to a decline in fish production (Birchenough et al. 2011). The cool copepod assemblages have moved towards the north due to the warming of the oceans. The waters get warmer and are replaced by warm water copepod assemblages having lower biomass than other small species. In the North Sea, Atlantic cod spawn in spring, and their larvae feed on large copepods. Climate change has shifted copepod biomass in the North Sea. The unavailability of large copepods has resulted in high mortality rates and an alarming drop in the recruitment of these fish (Beaugrand et al. 2003; Richardson 2008).

Pelagic fish stocks have a unique spatial and temporal distribution pattern associated with their bioclimatic niche. Shifts in primary and secondary production have consequences on the distribution range, migratory habits, and stock size of many marine fish species due to climate change (Brander 2010). Reviewing the published data on North Atlantic fish species representing varied biogeographic affinities, habitats, and body size supports the hypothesis that global warming results in the shift, abundance, and distribution of different fish species (Rijnsdorp et al. 2009). Changes in migration patterns have been observed due to changes in zooplankton productivity due to climate change. Climate change has affected the distribution and expansion of several fish species. The distribution of Lusitanian species like horse mackerel, sprat, and anchovy has augmented in recent decades, particularly in the Northern limit of their distribution areas, while Borealis like cod and plaice have decreased at the southern boundaries. Still, cod has increased in the northern limit. So far, the existing pieces of evidence suggest that climate-related changes can alter the process of recruitment as a result of higher survival in the pelagic egg or larval stage due to variations in the nursery habitats (Rijnsdorp et al. 2009).

Some fish stocks act as biological indicators of extreme climate-induced fluctuations that can be significantly affected. The reproductive success, population dynamics, migration patterns, and interactions between specific fish populations such as straddling pelagic stocks like herring, mackerel, capelin, blue whiting, sprat, anchovy, and sardine can show a most crucial shift. The most noticeable effect of climate change will be a poleward expansion (Perry et al. 2005).

A shift away from shallow coastal waters and semi-enclosed areas is expected into deeper, cooler waters due to rising temperatures. Mostly, fish tend to live near their tolerance limits comprising a range of factors. Therefore, an increase in temperature and acidity reduced dissolved oxygen, and changes in salinity may have deleterious effects on their populations (Lehodey et al. 2006; Brander 2010).

In addition to the change in species distribution, invasive species, and extinction, the body size of fish might be reduced and lower the impact of fish stock recruitment when sea temperatures are elevated (Barange and Perry 2009). The potential for significant change in species abundance and composition could affect the whole ecosystem and the fisheries that rely on it. Some important marine ecosystems such as mangroves, seagrass, and coral reefs are under tremendous stress due to habitat destruction by human interference, pollution, etc. Climate change may add more stress and ultimately bring about structural and behavioral change in the ecosystem (Ficke et al. 2007; Barange and Perry 2009; Brander 2010).

9 Impact on Aquaculture

Climate change, a threat to global food production, can damage the quality and quantity of fish production. Global fish production has progressed continuously, reaching 46% of the estimated figures. Global fish production is expected to increase from 46% to 53% in 2030. However, the changing climate poses a challenge for the sector's fast, sustainable growth to meet the food requirements of the rapidly growing human population. Aquaculture, the fastest-growing global food-producing sector, has also been affected by climate change. The sector seems to be at risk because the predicted effects of climate change are alarming (reviewed by Maulu et al. 2021). The impact of climate change on aquaculture has been extensively reviewed (Maulu et al. 2021). Most of the studies in climate change have established adverse effects, overlooking the positive ones. Climate change, directly and indirectly, affects aquaculture production (Handisyde et al. 2006; De Silva and Soto 2009). The direct effects influence the physical and physiology of finfish and shellfish stocks in production systems. At the same time, indirect may alter the primary and secondary productivity and structure of the ecosystems, input supplies, and services needed by fishers and aquaculture producers. Global climate has significantly affected fish growth vulnerability to diseases, time of spawning, and mortality at certain stages of the life cycle with economic impact and implications for the cultural process (Maulu et al. 2021).

Bivalve culture is a relatively attractive method of producing a high-quality, healthy, and sustainable protein source for the expanding human population and constitutes a significant proportion of global mariculture (Stewart-Sinclair et al. 2020). Climate change resulting in coastal water acidification could have a severe impact on the production of bivalves. It has been advocated that global warming can also be advantageous for aquaculture as it may promote larval settlement. Attachment of early-stage bivalves may result in better growth rates of some farmed species (Bell et al. 2013). However, the acidification of the marine environment and the impact thereof on marine finfish are still unclear. Fish embryos and larvae being delicate as compared with juveniles and adults would be harmed the most, due to alteration in growth rate as a consequence of acidification of the aquatic environment (Heuer and Grosell 2014). Life-threatening weather happenings may record an upsurge in the frequency of physiological impacts on metabolism because of the variations in salinity and temperature (Pörtner et al. 2014). Such occasions may result in escaping of fish from aquaculture facilities besides the impairment of the infrastructure. Elevated temperatures, salinities, and lack of rain because of El Nino in 2015–2016 might have caused the triggering of algal blooms in the fjords of Southern Chile, with an estimated loss of more than 12% in Chilean salmon production (León-Muñoz et al. 2018). Climate change can also indirectly impact the aquatic ecosystem, for example, it may alter the prevalence of fish diseases and the production of seeds for aquaculture. Further, an indirect consequence of climate change would result in inadequate availability of fishmeal, fish oil, and "trash" fish that would also affect feed production and in turn aquaculture (Brander 2010; Merino et al. 2012).

Prevalence and occurrence of diseases in fish are likely as warm water pathogens may dominate. For example, *Vibrio* species grow preferentially in warm waters (>15 °C) and at low salinity (<25 ppm); therefore, vibriosis may be affected by climate change. The consequences of climate change are predicted to be more on tropical marine ecosystems (Pörtner et al. 2014; Brumfield et al. 2021). About 80% of the 26 million tonnes of marine food fish produced in 2013 were raised in Asia. Climate change may impact food security by the middle of the twenty-first century, with South Asia as the most severely affected region. Exposure and sensitivity to changing climate would make Bangladesh, China, Indonesia, Philippines, and Vietnam highly vulnerable (Handisyde et al. 2006) besides Ecuador, Egypt, Norway, and Chile. A recent reconsideration of the elevated rates of sea level (DeConto and Pollard 2016) suggests that unabated GHG emissions would result in a contribution of an extra 1 m of rising by 2100 from the Antarctic alone, which would significantly increase the impacts on the mariculture in highly vulnerable countries. Therefore, poor planning and bad management in aquaculture could enhance the vulnerability of coastal communities to climate change.

10 Adaptations and Their Implications

Adaptation is the tuning of natural or human systems in response to an actual or an expected change. Effects that can moderate damage or exploit beneficial opportunities are essential as climatic stimuli lead to adaptation. Adaptation can be achieved by reducing risks and vulnerabilities, identifying opportunities, and capacity building at all geographical and social scales to cope with current and expected impacts. Some of these measures may help natural systems adapt, but the focus is on humans rather than natural adaptation.

Some broad adaptation strategies that can be kept going in the face of adversity with relevance to fisheries and aquaculture systems are:

- Monitoring, forecasting, early warning data systems, and adaptation could be helpful in generating as well as sharing information about climate change.
- Projections and impact assessments of regional and local climate may be investigated for finding solutions.
- Integration of ways to adapt to climate change in decision-making, policies and procedures,
- Sustaining and augmenting the flexibility of natural and human systems circumventing obstructions in adaptation.
- Responding firmly to societal inequality and dissemination of the effects due to climate change.

- Implementation of green taxes or trading systems as adaptive measures to evade undesirable effects of climate change.

The Food and Agriculture Organization (FAO) advocates the control and management of fisheries to uphold healthy and productive ecosystems (Cochrane et al. 2009) that ensures the upkeep of structure, practices, roles, and interfaces between the components of the ecosystem strategically including and maintaining biodiversity. In some cases, for example in coastal environments and ecosystems, restoration of the habitat may be essential as a part of an ecosystem approach (Koehn et al. 2020). Adaptive actions may assist in the conservation of climate-induced changes, particularly in species composition. Therefore, management requirements may be enforced to adjust and respond to climate-induced changes such as changes in distribution, species composition, or productivity (Cochrane et al. 2009). The ecosystem approach to aquaculture offers the opportunity to consider climate change in the sector's planning and the refinement of management practices to effectively address climate inconsistency and drifts at scales ranging from individual to farm or a selected area under management. Several studies have identified possible adaptation strategies for mangrove systems and the people that use them. These include creating awareness of the importance of such systems among local communities and leaders, identifying critical areas, and minimizing stress unrelated to climate. Other issues that require attention are maintaining ecosystem connectivity, coastal planning that facilitates emergency retreats to inland areas, developing alternative livelihoods, and restoring coastal ecosystems. Experience suggests that it is necessary to integrate adaptation to climate change with the broader policy agenda.

11 Conclusion

Empirical evidence reveals that the warming up of the ocean affects the dissemination and periodic patterns of invertebrates, fish, and mammals. Such tendencies can continue in the future and lead to significant changes in the ecosystems. Threats due to climate change increase the collective impacts of other anthropogenic activities like over-exploitation, habitat degradation, pollution, eutrophication, and the introduction of species. The phenomenon is more prominent in the seas and oceans, which severely affects fisheries and aquaculture, as shown by several studies. Global warming could rapidly dry the water resources and even increase the salinity of groundwater, which will be detrimental to freshwater fisheries, aquaculture, and agriculture.

Moreover, such water would limit industrial and domestic usage. Studies on climate change suggest that 60% of coral reefs could be lost by 2030 and that increased acidification of oceans from higher levels of atmospheric carbon dioxide may be a contributing factor. Increasing temperature can also alter the physiological functions (thermal tolerance, growth, metabolism, food consumption, reproductive success, etc.) of the fish body to maintain homeostasis with the environment.

Adverse impacts of climate change are also putting enormous stresses on the lives and livelihoods of the people engaged in fisheries. It is foreseen that changes in intensity and seasonality of climate patterns would have serious consequences on fisheries. For instance, maritime territories extending 200 nautical miles from a country's coastline are exclusive economic zones (EEZs) with sovereign rights over natural resources. Impacts of climate change on fisheries potential of maritime territories are expected to be $<10\%$ between 2005 and 2050 for most EEZs, with an overall increase in production at mid to high latitudes and a decrease at low latitudes (Westerveld 2020). Therefore, managing existing fisheries and utilizing best management practices should counterbalance negating impacts of climate change on the potential of fisheries under an ecosystem-based approach. It is evident from the information that changes due to global warming will potentially have both favorable and unfavorable impacts on aquaculture. However, data indicate that adverse changes are likely to outweigh favorable ones, particularly in developing countries where adaptive capacity is the weakest. Adaptation to climate change must be undertaken within the multifaceted context, and any additional measures or actions taken in response to climate change should be a complement. Communities could help adapt to climate change by developing policies and programs to improve the resilience of natural resources through assessments of risk and vulnerability by increasing awareness of the impacts of climate change and by strengthening key institutions that would help the communities' adaptation. In this context, adopting climate resilience as an adaptation strategy will help meet the livelihood security of stakeholders associated with fisheries and aquaculture. The ecosystem approach to aquaculture offers the opportunity to consider climate change in the sector's planning and the development of management measures. Social and economic aspects and resource productivity need to be adapted for the management of fisheries to mitigate climate change. Moreover, ecological and human well-being are also warranted for the sustainability of aquatic resources. Advanced techniques and protocols need to be implemented for combating the changing climatic conditions.

References

Adams RM, Twiss MR, Driscoll CT (2009) Patterns of mercury accumulation among seston in lakes of the Adirondack Mountains, New York. Environ Sci Technol 43(13):4836–4842

Alfonso S, Gesto M, Sadoul B (2021) Temperature increase and its effects on fish stress physiology in the context of global warming. J Fish Biol 98(6):1496–1508

Amap/UNEP (2015) Global mercury modelling: update of modelling results in the global mercury assessment 2013. Arctic Monitoring and Assessment Programme, UNEP Chemicals Branch, Oslo, Geneva

Báez JC, Gimeno L, Real R (2021) North Atlantic Oscillation and fisheries management during global climate change. Rev Fish Biol Fish 31(2):319–336

Barange M, Perry RI (2009) Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture. In: Cochrane K, De Young C, Soto D, Bahri T (eds) Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper. No. 530. FAO, Rome, pp 7–106

Bard B, Kieffer J (2019) The effects of repeat acute thermal stress on the critical thermal maximum (CTmax) and physiology of juvenile short-nose sturgeon Acipenser brevirostrum. Can J Zool 97:567–572

Beaugrand G, Brander KM, Lindley JA, Souissi S, Reid PC (2003) Plankton effect on cod recruitment in the North Sea. Nature 426(6967):661–664

Bell JD, Ganachaud A, Gehrke PC, Griffiths SP, Hobday AJ, Hoegh-Guldberg O, Johnson JE, Le Borgne R, Lehodey P, Lough JM, Matear RJ (2013) Mixed responses of tropical Pacific fisheries and aquaculture to climate change. Nat Clim Chang 3(6):591–599

Birchenough SN, Degraer S, Reiss H, Craeymeersch JAM, de Mesel IG (2011) Responses of marine benthos to climate change. In: ICES status report on climate change in the North Atlantic, vol 310. ICES, Copenhagen, pp 123–146

Boyce DG, Lewis MR, Worm B (2010) Global phytoplankton decline over the past century. Nature 466(7306):591–596

Brander K (2010) Impacts of climate change on fisheries. J Mar Syst 79(3–4):389–402

Brumfield KD, Usmani M, Chen KM, Gangwar M, Jutla AS, Huq A, Colwell RR (2021) Environmental parameters associated with incidence and transmission of pathogenic Vibrio spp. Environ Microbiol 23(12):7314–7340

Cermeno P, Dutkiewicz S, Harris RP, Follows M, Schofield O, Falkowski PG (2008) The role of nutricline depth in regulating the ocean carbon cycle. Proc Natl Acad Sci U S A 105:20344–20349

Chen Y, Todd AS, Murphy MH, Lomnicky G (2016) Anticipated water quality changes in response to climate change and potential consequences for inland fishes. Fisheries 41(7):413–416

Clarkson TW (1993) Mercury: major issues in environmental health. Environ Health Perspect 100: 31–38

Clow DW (2010) Changes in the timing of snowmelt and streamflow in Colorado: a response to recent warming. J Clim 23(9):2293–2306

Cochrane K, De Young C, Soto D, Bahri T (2009) Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper. No. 530. FAO, Rome. 212 p

Crowley TJ (2000) Causes of climate change over the past 1000 years. Science 289(5477):270–277

De Silva SS, Soto D (2009) Climate change and aquaculture: potential impacts, adaptation and mitigation. In: Climate change implications for fisheries and aquaculture: overview of current scientific knowledge, vol 530. FAO Fisheries and Aquaculture Technical Paper, pp 151–212

DeConto RM, Pollard D (2016) Contribution of Antarctica to past and future sea-level rise. Nature 531(7596):591–597

Dengiz Balta Z, Akhan S, Balta F (2017) The physiological stress response to acute thermal exposure in Black Sea trout (Salmo trutta Labrax Pallas, 1814). Turk J Vet Anim Sci 41:400–406

Dittman JA, Driscoll CT (2009) Factors influencing changes in mercury concentrations in lake water and yellow perch (Perca flavescens) in Adirondack lakes. Biogeochemistry 93(3):179–196

Doney SC, Fabry VJ, Feely RA, Kleypas JA (2009) Ocean acidification: the other CO2 problem. Annu Rev Mar Sci 1:169–192

Dulvy NK, Rogers SI, Jennings S, Stelzenmüller V, Dye SR, Skjoldal HR (2008) Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. J Appl Ecol 45(4):1029–1039

Evans CD, Monteith DT, Cooper DM (2005) Long-term increases in surface water dissolved organic carbon: observations, possible causes and environmental impacts. Environ Pollut 137 (1):55–71

Falkowski PG (1994) The role of phytoplankton photosynthesis in global biogeochemical cycles. Photosynth Res 39:235–258

Falkowski P (2012) Ocean science: the power of plankton. Nature 483:S17–S20

Ficke AD, Myrick CA, Hansen LJ (2007) Potential impacts of global climate change on freshwater fisheries. Rev Fish Biol Fish 17(4):581–613

Fitzgerald WF, Lamborg CH (2014) Geochemistry of mercury in the environment. In: Holland HD, Turekian KK (eds) Treatise on Geochemistry, 2nd edn. Elsevier, Oxford, pp 91–129

Gribbin J (1988) The greenhouse effect. New Sci 120:1–4

Grigas D, Lehrter J, Cebrian J, Chen Y, Ehmen B, Woodrey M (2015) Effects of stormwater pipe size and rainfall on sediment and nutrients delivered to a coastal bayou. Water Environ Res 87 (9):796–804

Handisyde NT, Ross LG, Badjeck MC, Allison EH (2006) The effects of climate change on world aquaculture: a global perspective. In: Aquaculture and Fish Genetics Research Programme, Stirling Institute of Aquaculture. Final Technical Report, DFID, Stirling, 151pp

Harrod C, Ramírez A, Valbo-Jørgensen J, Funge-Smith S (2019) How climate change impacts inland fisheries. In: Impacts of climate change on fisheries and aquaculture, p 375

Hegerl GC, Brönnimann S, Cowan T, Friedman AR, Hawkins E, Iles C, Müller W, Schurer A, Undorf S (2019) Causes of climate change over the historical record. Environ Res Lett 14(12): 123006

Heuer RM, Grosell M (2014) Physiological impacts of elevated carbon dioxide and ocean acidification on fish. Am J Phys Regul Integr Comp Phys 307(9):R1061–R1084

Huertas IE, Rouco M, Lopez-Rodas V, Costas E (2011) Warming will affect phytoplankton differently: evidence through a mechanistic approach. Proc R Soc B Biol Sci 278 (1724):3534–3543

Jones PD, Mann ME (2004) Climate over past millennia. Rev Geophys 42(2):1

Jonkers L, Hillebrand H, Kucera M (2019) Global change drives modern plankton communities away from the pre-industrial state. Nature 570(7761):372–375

Joshi KD, Das SCS, Pathak RK, Khan A, Sarkar UK, Roy K (2018) Pattern of reproductive biology of the endangered golden mahseer Tor putitora (Hamilton 1822) with special reference to regional climate change implications on breeding phenology from lesser Himalayan region, India. J Appl Anim Res 46(1):1289–1295

Kärcher O, Flörke M, Markovic D (2021) Different life stage, different risks: thermal performance across the life cycle of Salmo trutta and Salmo salar in the face of climate change. Ecol Evol 11: 8941

Kirkland J, Flitcroft R, Grant G (2021) Let the fish do the talking: how fish behavior is linked to patterns of temperature and stream discharge. In: Science findings, vol 240. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, pp 1–5

Kitaysky AS, Golubova EG (2000) Climate change causes contrasting trends in reproductive performance of planktivorous and piscivorous alcids. J Anim Ecol 69(2):248–262

Koehn JD, Raymond SM, Stuart I, Todd CR, Balcombe SR, Zampatti BP, Bamford H, Ingram BA, Bice CM, Burndred K, Butler G (2020) A compendium of ecological knowledge for restoration of freshwater fishes in Australia's Murray–Darling Basin. Mar Freshw Res 71(11):1391–1463

Kweku DW, Bismark O, Maxwell A, Desmond KA, Danso KB, Oti-Mensah EA, Quachie AT, Adormaa BB (2017) Greenhouse effect: greenhouse gases and their impact on global warming. J Sci Res Rep:1–9

Lehodey P, Alheit J, Barange M, Baumgartner T, Beaugrand G, Drinkwater K, Fromentin JM, Hare SR, Ottersen G, Perry RI, Roy CVDL (2006) Climate variability, fish, and fisheries. J Clim 19(20):5009–5030

León-Muñoz J, Urbina MA, Garreaud R, Iriarte JL (2018) Hydroclimatic conditions trigger record harmful algal bloom in western Patagonia (summer 2016). Sci Rep 8(1):1–10

Leppi JC, DeLuca TH, Harrar SW, Running SW (2012) Impacts of climate change on August stream discharge in the Central-Rocky Mountains. Clim Chang 112(3):997–1014

Mast MA, Turk JT, Clow DW, Campbell DH (2011) Response of lake chemistry to changes in atmospheric deposition and climate in three high-elevation wilderness areas of Colorado. Biogeochemistry 103(1):27–43

Maulu S, Hasimuna OJ, Haambiya LH, Monde C, Musuka CG, Makorwa TH, Munganga BP, Phiri KJ, Nsekanabo JDM (2021) Climate change effects on aquaculture production: sustainability implications, mitigation, and adaptations. Front Sustain Food Syst 5:609097

Merino G, Barange M, Blanchard JL, Harle J, Holmes R, Allen I, Allison EH, Badjeck MC, Dulvy NK, Holt J, Jennings S (2012) Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate? Glob Environ Chang 22(4):795–806

Miller LP, Matassa CM, Trussell GC (2014) Climate change enhances the negative effects of predation risk on an intermediate consumer. Glob Chang Biol 20(12):3834–3844

Mcclanahan TR, Cinner J (2012) Adapting to a changing environment: confronting the consequences of climate change. OUP, New York, NY

Myers BJ, Lynch AJ, Bunnell DB, Chu C, Falke JA, Kovach RP, Krabbenhoft TJ, Kwak TJ, Paukert CP (2017) Global synthesis of the documented and projected effects of climate change on inland fishes. Rev Fish Biol Fish 27(2):339–361

Nerem RS, Beckley BD, Fasullo JT, Hamlington BD, Masters D, Mitchum GT (2018) Climate-change–driven accelerated sea-level rise detected in the altimeter era. Proc Natl Acad Sci 115(9):2022–2025

Nikinmaa M (2013) Climate change and ocean acidification—interactions with aquatic toxicology. Aquat Toxicol 126:365–372

Null SE, Ligare ST, Viers JH (2013) A method to consider whether dams mitigate climate change effects on stream temperatures. J Am Water Resour Assoc 49(6):1456–1472

O’Mara K, Venarsky M, Stewart-Koster B, McGregor GB, Schulz C, Kainz M, Marshall J, Bunn SE (2021) Connectivity of fish communities in a tropical floodplain river system and predicted impacts of potential new dams. Sci Total Environ 788:147785

Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421:37–42

Paukert CP, Lynch AJ, Beard TD, Chen Y, Cooke SJ, Cooperman MS, Cowx IG, Ibengwe L, Infante DM, Myers BJ, Nguyễn HP (2017) Designing a global assessment of climate change on inland fishes and fisheries: knowns and needs. Rev Fish Biol Fish 27(2):393–409

Perry AL, Low PJ, Ellis JR, Reynolds JD (2005) Climate change and distribution shifts in marine fishes. Science 308(5730):1912–1915

Pörtner H-O, Karl DM, Boyd PW, Cheung W, Lluch-Cota SE, Nojiri Y, Schmidt DN et al (2014) Ocean systems. In: Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, pp 411–484

Rahmstorf S (2010) A new view on sea level rise. Nat Clim Chang 1(1004):44–45

Reba ML, Daniels M, Chen Y, Sharpley A, Bouldin J, Teague TG, Daniel P, Henry CG (2013) A statewide network for monitoring agricultural water quality and water quantity in Arkansas. J Soil Water Conserv 68(2):45A–49A

Richardson AJ (2008) In hot water: zooplankton and climate change. ICES J Mar Sci 65(3):279–295

Rijnsdorp AD, Peck MA, Engelhard GH, Möllmann C, Pinnegar JK (2009) Resolving the effect of climate change on fish populations. ICES J Mar Sci 66(7):1570–1583

Roessig JM, Woodley CM, Cech JJ, Hansen LJ (2004) Effects of global climate change on marine and estuarine fishes and fisheries. Rev Fish Biol Fish 14(2):251–275

Rogora M, Mosello R, Arisci S (2003) The effect of climate warming on the hydrochemistry of alpine lakes. Water Air Soil Pollut 148(1):347–361

Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA (2003) Fingerprints of global warming on wild animals and plants. Nature 421:57–60

Shindell DT, Schmidt GA, Mann ME, Rind D, Waple A (2001) Solar forcing of regional climate change during the Maunder Minimum. Science 294(5549):2149–2152

Stern DI, Kaufmann RK (2014) Anthropogenic and natural causes of climate change. Clim Chang 122(1):257–269

Stevenson JC, Kearny MS, Kock EW (2002) Impacts of sea level rise on tidal wetlands and shallow water habitats: a case study from Chesapeake Bay. In: McGinn NA (ed) Fisheries in a changing climate. American Fisheries Society Symposium 32, Bethesda, MD, pp 23–36

Stewart-Sinclair PJ, Last KS, Payne BL, Wilding TA (2020) A global assessment of the vulnerability of shellfish aquaculture to climate change and ocean acidification. Ecol Evol 10(7): 3518–3534

Thorstad EB, Bliss D, Breau C, Damon-Randall K, Sundt-Hansen LE, Hatfield EM, Horsburgh G, Hansen H, Maoiléidigh NÓ, Sheehan T, Sutton SG (2021) Atlantic salmon in a rapidly changing environment—facing the challenges of reduced marine survival and climate change. Aquat Conserv Mar Freshwat Ecosyst 31:2654

Thuiller W (2007) Climate change and the ecologist. Nature 448(7153):550–552

Timoner P, Fasel M, Ashraf Vaghefi SS, Marle P, Castella E, Moser F, Lehmann A (2021) Impacts of climate change on aquatic insects in temperate alpine regions: complementary modeling approaches applied to Swiss rivers. Glob Chang Biol 27:3565

Todd AS, Manning AH, Verplanck PL, Crouch C, McKnight DM, Dunham R (2012) Climate-change-driven deterioration of water quality in a mineralized watershed. Environ Sci Technol 46 (17):9324–9332

Wallington TJ, Srinivasan J, Nielsen OJ, Highwood EJ (2009) Greenhouse gases and global warming. Environ Ecol Chem 1:36

Walther G, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin J, Hoegh-Guldberg-O, Bairlein F (2002) Ecological responses to recent climate change. Nature 416:389–395

Westerveld L (2020) The potential impacts of climate change on maritime boundaries and exclusive economic zones, three GIS scenarios for 20 jurisdictions in the western and central Pacific region. Master's thesis, The University of Bergen

Whitfield AK (2021) Estuaries–how challenging are these constantly changing aquatic environments for associated fish species? Environ Biol Fish 104:1–12

Wilkinson CP (1998) The 1997-1998 mass bleaching event around the world

Williamson P, Guinder VA (2021) Effect of climate change on marine ecosystems. In: The impacts of climate change, pp 115–176

Winslow JC, Hunt ER Jr, Piper SC (2003) The influence of seasonal water availability on global C3 versus C4 grassland biomass and its implications for climate change research. Ecol Model 163(1–2):153–173

Zaidel PA, Roy AH, Houle KM, Lambert B, Letcher BH, Nislow KH, Smith C (2021) Impacts of small dams on stream temperature. Ecol Indic 120:106878

Climate Change: Stressor on Marine Buffer System

Suchismita Jana and Shirsak Mondal

Abstract

Oceans are natural carbonate buffer systems and work as a carbon sink in the environment which is much larger than the atmospheric and terrestrial carbon content. The global carbon cycle is maintained by the continuous gaseous exchange during photosynthesis and respiration. The atmospheric CO_2 also gets dissolved into the ocean water and forms weak carbonic acid. Thus, ocean water is a mixture of various numerous weak acids and bases and stays in contact with the atmosphere and other minerals as sediments. All of them together make the ocean an excellent buffer for neutralizing small changes in its composition. But the recent increase in industrialization and anthropogenic activities are causing the increase in atmospheric CO_2 and climate change. More atmospheric CO_2 is being dissolved in ocean water and carbon is being released from oceanic carbon sink making the ocean more acidic. Since industrialization, ocean water pH has dropped by 0.1 unit which indicated approximately a 30% increase in hydrogen ion concentration and 16% decrease in carbonate ion concentration relative to the preindustrial value. As a result of ocean acidification, there are devastating effects on ocean biota. An increase in sea surface temperature and deoxygenation are other climate change-related stressors on the ocean system.

Keywords

Carbonate buffer system · Climate change · Ocean acidification · Sea surface temperature · Deoxygenation

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1 Introduction

Oceans are well-known buffer systems, defined as carbonate buffer systems, and act as a reservoir for carbon. This reserved carbon is more than terrestrial and atmospheric carbon content and helps to control the global carbon cycle. This carbon dioxide-carbonate system works as a sink for atmospheric CO_2 and absorbs more CO_2 than they release into the atmosphere (Turley et al. 2010). The ocean surface pH and alkalinity have been unchanged for the last 750,000 years (NIWA n.d.). Plants and animals add CO_2 to the atmosphere by respiration and again balance by plant photosynthesis. There is also a continuous gaseous carbon exchange between the atmosphere and the ocean. The CO_2 form carbonic acid in contact with ocean water. This weak acid is neutralized in the ocean carbonate buffer system. In the last few decades, there is a constant increase in atmospheric CO_2 content because of the rapid anthropogenic activities, abundant fossil fuel burning, and changes in land use. This leads to carbon pollution both in the atmosphere and the ocean. Increasing CO_2 content is causing warming of both the atmosphere and ocean system and ultimately changing the physico-chemical phenomena that usually happen and control the ocean buffer system (Climate Reality 2016).

2 Ocean Alkalinity

Alkalinity is the buffering capacity of any water body. It can be defined as the excess number of bases or proton acceptors over acids or proton donors in a water system. In the ocean system, several factors can contribute to controlling and affecting the alkalinity. Where the oxidation process can reduce the alkalinity, anaerobic reactions can increase the water's alkalinity. There are numerous reports about ocean alkalinity and its interpretations in different ways (Middelburg et al. 2020). Dickson (1992) came up with an extensive conclusion regarding the relation between chemical models of marine water, its relation with alkalinity, and the measuring of alkalinity. The ocean alkalinity is balanced by various factors such as ions released into the open ocean by weathering of rocks (Mackenzei and Garrels 1966) and again deposition and precipitation of sediment after the calcification process. This phenomenon is generally represented as (Urey 1952):

$$\mathrm{CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2}$$

This equation establishes the transfer and removal of atmospheric CO_2 in the form of sediment. Middelburg et al. (2020) described possible factors that affect or balance the ocean alkalinity directly which are alkalinity sources and alkalinity sinks:

Alkalinity sources are riverine DIC (dissolved inorganic carbon), riverine PIC (particulate inorganic carbon), submarine groundwater, submarine silicate, sulfur burial, denitrification, and organic matter burial (Fig. 1).

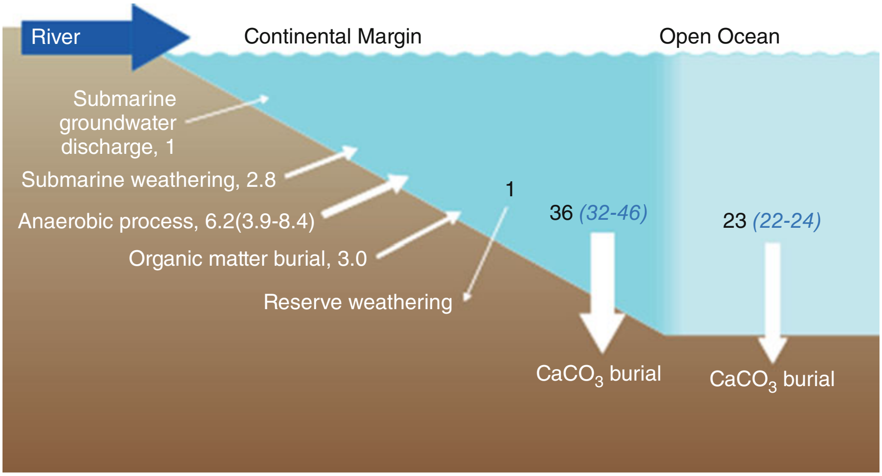

Fig. 1 Ocean alkalinity balance (fluxes are in Tmol/year). (Source: Middelburg et al. 2020)

Alkalinity sinks are open ocean carbonate burial, ocean margin carbonate burial, and reverse weathering.

Ocean alkalinity can be measured and referred to as titration alkalinity and charge balance alkalinity (CBA). The understanding of these alkalinities is used to quantify calcification and carbonate dissolution and also helps to determine the impact of biogeochemical processes on components of the carbon dioxide system in the ocean. Titration alkalinity or as known as total alkalinity is the mostly used alkalinity for experiment and observational purposes in the ocean. CBA is used for theoretical, modeling, and geological studies. CBA is essential for quantifying the buffering capacity and pH changes in natural environments and this is often used to denote excess negative charge in the freshwater system (Turchyn and DePaolo 2019).

3 Marine Buffer System

Ocean water is a mixture of numerous weak acids and bases and stays in contact with the atmosphere and other minerals as sediments. There is a continuous exchange of various gases between ocean water surface and atmosphere. All of them together have the potential to react if there is any physical or chemical variation in the composition. In general, ocean water having multiple weak acids, bases, and minerals has an excellent capacity to buffering any small changes in the acidity of alkalinity by transforming the proton (Middelburg et al. 2020). Ocean alkalinity is the central idea to understanding its buffering capacity and its role in CO_2 uptake. Seawater also contains multiple sensitivity and buffering factors which are just opposite to each other. Sensitivity factors are those which induce changes in chemical features but buffering factors restrain that change. Buffering capacity of seawater is homogenous and heterogeneous. Homogenous buffering is more instantaneous and spatially distributed in the ocean. Heterogenous buffering occurs due to the dissolution, precipitation, and deposition of minerals and sediments on the seafloor (Archer et al. 1998; Boudreau et al. 2018).

4 Climate Change

According to United Nations (n.d.), climate change is a long-term change in temperature and weather patterns. These changes are mostly driven by anthropogenic activities. After the 1800s, rapid industrialization triggered the changing of weather patterns. Excess carbon pollution is the prime reason behind this rapid climate change (Fig. 2). As a result of that, our planet Earth is now 1.1 °C hotter than that was in the 1800s.

Fossil fuel burning and changes in land-use patterns are erupting CO_2 and other greenhouse gases. These gases work as a shield and help in trapping the reflected sunlight. This incident is causing global warming and ultimately leading to changing the climatic pattern (The Royal Society, US National Academy of Sciences 2020). Atmospheric CO_2 has increased by upto 49% from the preindustrial concentration of about 280 ppm. As per the report by Siegenthaler (2005), the recent atmospheric CO_2 increase is almost 100 times faster than what occurred in the last 650,000 years.

5 Ocean Acidification

The ocean has a vast contribution to the global carbon cycle. Its inorganic carbon reservoir is roughly 37,400 Gt (10^{15} g), which is about 50 times and more than 18 times higher than that of the atmosphere and terrestrial realm, respectively (Fig. 3). Ocean water acts as a sink for CO_2 due to its carbonate buffer system which is the

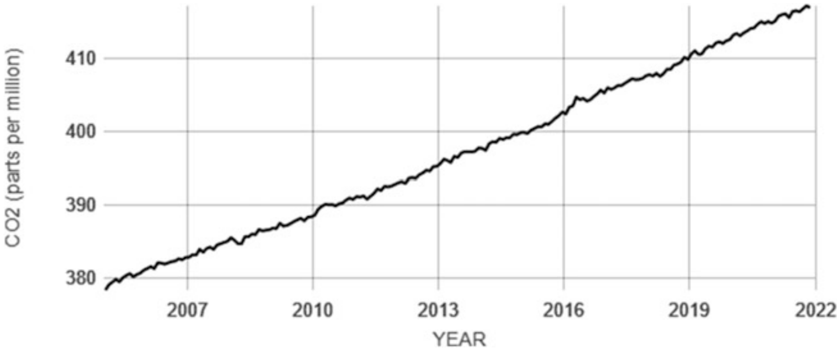

Fig. 2 Change in carbon dioxide concentration in the atmosphere globally. (Source: climate.nasa.gov, NASA n.d.)

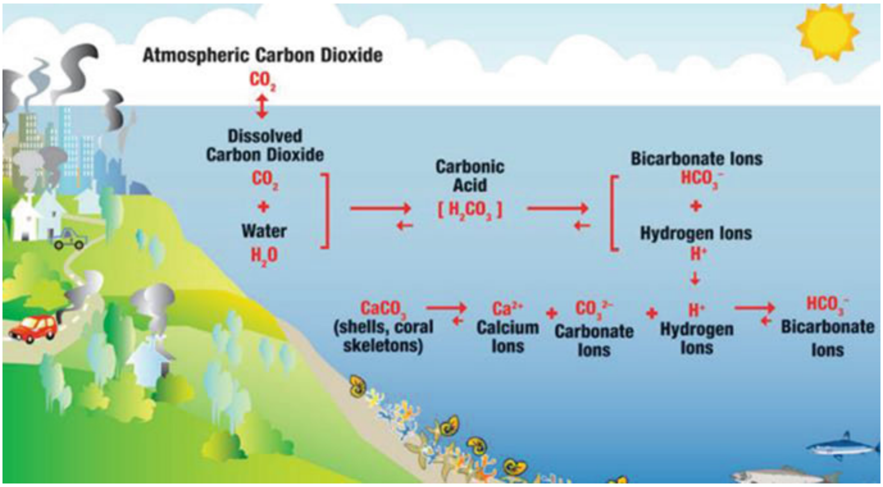

Fig. 3 Chemical reactions involve ocean acidification. (Source: The National Academies 2013)

result of the reaction of water with CO_2 forming carbonic acid, bicarbonate, and carbonate ions (Boudreau et al. 2018). Since industrialization, the ocean has played an important role in uptaking 28–34% of the CO_2 produced by anthropogenic activities. Within this period, ocean water pH has dropped by 0.1 unit which indicated approximately a 30% increase in hydrogen ion concentration and a 16% decrease in carbonate ion concentration relative to the preindustrial value (Turley et al. 2010). Researchers predicted more pH increase which is about 0.3–0.4 units by the end of this century (Caldeira et al. 2007). This rapid change in ocean water pH has not occurred in the last 20 million years of Earth's history. There is a series of chemical reactions that involve when then atmospheric CO_2 came in contact with ocean water and getting absorbed.

The ocean water stays in equilibrium with available carbon and bicarbonate ions where Ω is the calcium carbonate saturation state:

$$\Omega = \left[\mathrm{Ca}^{2+}\right]\left[\mathrm{CO}_2{}^{-3}\right]/K_{\mathrm{sp}}$$

Here, K_{sp} is the stoichiometric solubility product for $CaCO_3$; $[Ca^{2+}]$ and $[CO_2{}^{-3}]$ are the in situ calcium and carbonate concentrations (Guinotte and Fabry 2008). When the atmospheric CO_2 reacts with ocean water it first forms carbonic acid (H_2CO_3) which subsequently dissociates into H^+ ions and bicarbonate ions. Thus, there is an increase in H^+ ion concentration. These again react with available carbonate ions ($CO_3{}^{2-}$) and form more bicarbonate ions. These incidents lead to a shift in the form of inorganic carbon storage in the ocean (Lenton et al. 2018). Thus, a reduction in the carbonate ions $[CO_2{}^{-3}]$ concentration also leads to decreasing calcium carbonate saturation state (Ω) (Guinotte and Fabry 2008).

6 The Rise in Sea Surface Temperature

Climate change affects the marine environment in various ways. One of these is the rise in sea surface temperature. The increased fossil fuel burning and land-use change have led to the emission of excess greenhouse gases which mostly are CO_2. These gases trap the reflected energy in the atmosphere and the rest gets trapped in the ocean. The heat capacity of water determines its heat-absorbing capacity. Substances that have higher heat capacity require a larger amount of heat to increase a small amount in temperature. The water has 1000 times higher heat capacity than the air which helps in absorbing about 90% of additional heat (Sutton 2018). Bindoff et al. (2007) reported about 20 times more heat absorption by ocean water than the atmosphere since the 1960s. As per reports, this heat led to a globally averaged SST increase of ~0.67 °C from 1901 to 2005 with a warming rate of 0.06 °C/decade (Cravatte et al. 2009).

7 Oxygen Depletion

Another adverse effect of climate change on the ocean is oxygen depletion. Oxygen is a crucial element for marine life, to live and breathe. The recent event of climate change and global warming are causing changes in the gaseous composition of ocean water and ultimately deoxygenation. Climate change and sea surface temperature change have reduced the oxygen-holding capacity of ocean water. The ocean currents are also changing along with strongly stratified ocean water columns which cause less mixing of water and a lower amount of oxygen content in the deep ocean (O'Boyle 2020). Since the 1950s the oceans worldwide have lost about 2% of total dissolved oxygen expected to lose about 3–4% of dissolved oxygen. The reason behind this phenomenon is mainly climate change and global and ocean warming.

8 Impact on Marine Ecosystem

Climate change and related threats like ocean acidification, rise in ocean surface temperature, and deoxygenation have devastating effects on marine lives and the environment. It has been projected that these phenomena are affecting all areas of the ocean from the coastal to the deep-sea floor (Feely et al. 2009). The changes in the carbonate buffer chemistry of ocean water may disturb the calcification process of organisms, accelerate the dissolution of calcifying organisms and their other metabolic activities, acid-base regulations, blood circulation, also the nervous system of the organisms (Frommel et al. 2012). Such an important calcifying organism is coral which is severely under the stress of ocean acidification. The decreased pH of the ocean reduced the ability of reef-building corals to form the skeleton. Albright et al. (2010) revealed in their paper that ocean acidification affects the fertilization, settlement, and growth of reef-building corals thus reducing their recovering capacity from any disturbance. It is predicted that by the end of this century, the coral reef will erode faster than they could rebuild again and thus affecting the habitat of estimated one million species (Kibria 2015). Likewise, other calcifying organisms like sea urchins, nematodes, bivalves, and gastropods also get affected by ocean acidification. About 62% reduced growth rate have been found in sea urchin due to ocean acidification (Hendriks et al. 2010). Changing ocean pH has also affected the calcifying plankton like Coccoolithophores (unicellular calcifying phytoplankton) and foraminifera (calcifying protozoans). This cascading effect on the base level organism of the food chain in a marine environment can alter the species composition of the world's ocean (Kibria 2015). However, Hendriks et al. (2010) reported the beneficial effects of ocean acidification. They reported a higher growth rate of seaweed and seagrasses due to increased levels of dissolved CO_2 in the water.

The rise in sea surface temperature has a detrimental effect on marine biodiversity and is predicted to reduce the primary productivity and increase consumption and cycling of the organic matter on the ocean surface through heterotrophic processes and overall reduction of carbon export to the deep sea. The rise in ocean temperature is also helping in the redistribution of ocean biodiversity. For example, there is more plankton in the arctic. The temperature rise has also caused the sea level rise which is affecting mangroves, and corals by hampering their biology (Laffoley and Baxter 2016).

9 Impact on Human Health

Human health and well-being are directly related to the hydrosphere or the ocean. The ocean has provided humans with food, medication, and mental as well as physical health benefits. It also helps to control climate change to a certain extent and in coastal protection. Ocean acidification can negatively impact human health in four possible ways (Fig. 4). These are: (a) through malnutrition and poisoning by altering the food quantity and quality; (b) through respiratory issues by altering the air quality; (c) through the impact on mental health by modifying and altering the natural space; (d) through the decreased opportunity to obtain the natural medicines and cures. The effects of ocean acidification are not experienced singularly. Rather they show combined effects and affect us in various ways. It can be said that the effects of ocean acidification are the outcome of various complex combinations of linkages (Falkenberg et al. 2020).

10 Conclusion

Climate change is affecting the land and ocean equally and causing the warming worldwide. It also is the main reason behind the excessive increase in the atmospheric CO_2 content which is ultimately altering the ocean pH. Though ocean acidification increases the direct impact on a specific group of organisms, it ends up impacting every organism to a certain extent (Laffoley and Baxter 2016). Along with other climate-related stressors like sea surface temperature increase, and oxygen

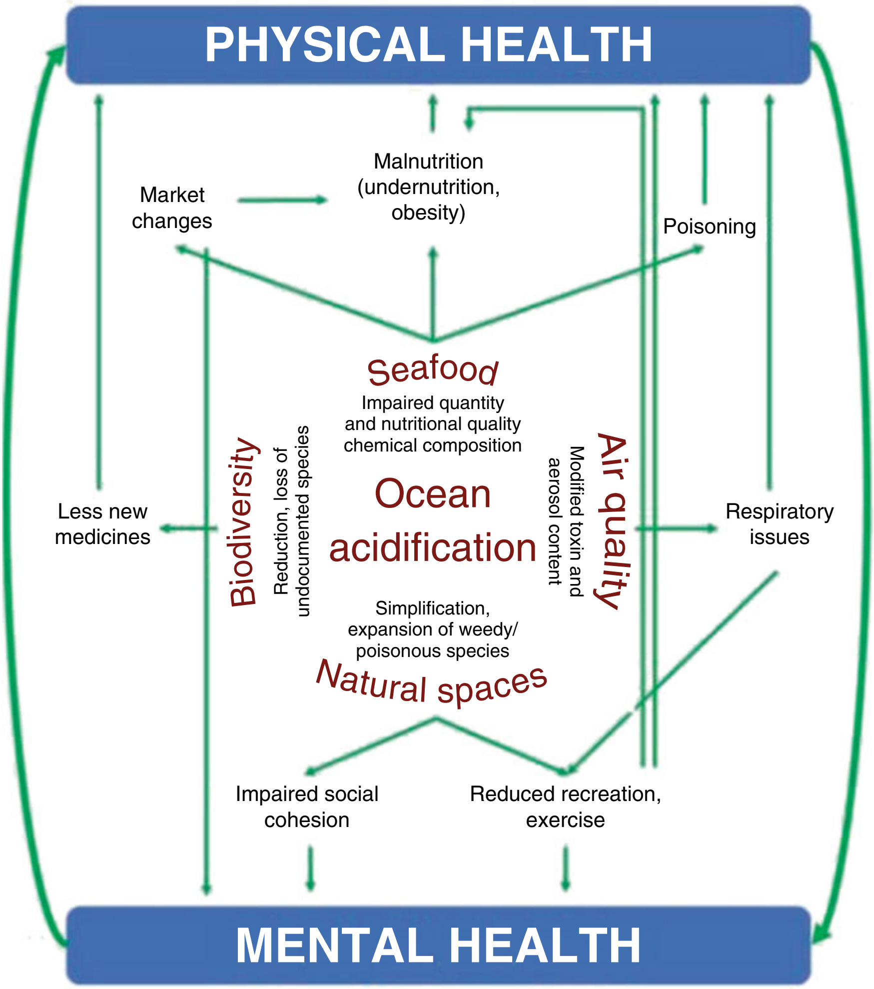

Fig. 4 Effects of ocean acidification on human health. (Source: Falkenberg et al. 2020)

depletion, the adverse effect of ocean acidification becomes more intensive (Falkenberg et al. 2020). Laffoley and Baxter (2016) suggested a few measures to control the uncontrolled climate change-related stressors on the marine environment which are: (a) there is a knowledge gap about the severity of impact due to the climate change-related stressor on the ocean system, which should come in people's attention; (b) there is an urgent need of taking serious actions and policies to redeem the adverse impacts; (c) a re-evaluation of risks to the environment and human beings and an analysis of economic impact due to the changes in the ocean buffer system are needed; (d) last but not least, the input of greenhouse gases mainly CO_2 into the atmosphere should be cut off as much as possible.

References

Albright R, Mason B, Miller M, Langdon C (2010) Ocean acidification compromises recruitment success of the threatened Caribbean coral *Acropora palmata*. PNAS 107:20400–20404

Archer D, Kheshgi H, Maier-Reimer E (1998) Dynamics of fossil fuel CO_2 neutralization by marine $CaCO_3$. Glob Biogeochem Cycles 12:259–276

Bindoff NL, Willebrand J, Artale V, Cazenave A, Gregory J, Gulev S, Hanawa K, Le Quéré C, Levitus S, Nojiri Y, Shum CK, Talley LD, Unnikrishnan A (2007) Observations: oceanic climate change and sea level. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Boudreau BP, Middelburg JJ, Luo Y (2018) The role of calcification in carbonate compensation. Nat Geosci 11:894–900

Caldeira K, Archer D, Barry JP, Bellerby RGJ, Brewer PG, Cao L, Dickson AG, Doney SG, Elderfield H, Fabry VJ, Feely RA, Gattuso JP, Haugan PM, Guldberg OH, Jain AK, Kleypas JA, Langdon C, Or JC, Ridgwell A, Sabine CL, Seibel BA, Shirayama Y, Turley C, Watson AJ, Zeebe REM (2007) Comment on "Modern-age buildup of CO2 and its effects on seawater acidity and salinity" by Hugo A. Loáiciga. Geophys Res Lett 34:1–3

Climate Reality (2016) Global warming's evil twin: ocean acidification. In: The climate reality project. https://www.climaterealityproject.org/blog/global-warming-ocean-acidification

Cravatte S, Delcroix T, Zhang D, McPhaden M, Leloup J (2009) Observed freshening and warming of the western Pacific Warm Pool. Clim Dyn 33:565–589

Dickson AG (1992) The development of the alkalinity concept in marine chemistry. Mar Chem 40: 49–63

Falkenberg LJ, Bellerby RGJ, Connell SD, Fleming LE, Maycock B, Russell DB, Sullivan FJ, Dupont S (2020) Ocean Acidification and Human Health. Int J Environ Res Public Health 17: 4563

Feely RA, Doney SC, Cooley SR (2009) Ocean acidification: present conditions and future changes in a high-CO_2 world. Oceanography 22:36–47

Frommel AY, Maneja R, Lowe D, Malzahn AM, Geffen AJ, Folkvord A, Piatkowski U, Reusch TBH, Clemmesen C (2012) Severe tissue damage in Atlantic cod larvae under increasing ocean acidification. Nat Clim Chang 2012:42–46

Guinotte JM, Fabry VJ (2008) Ocean acidification and its potential effects on marine ecosystems. Ann N Y Acad Sci 1134:320–342

Hendriks IE, Duarte CM, Alvarez M (2010) Vulnerability of marine biodiversity to ocean acidification: a meta-analysis. Estuar Coast Shelf Sci 86:157–164

Kibria G (2015) Ocean acidification and its impact on marine biodiversity, seafood security & livelihoods - a short review. Research Gate Online. https://www.researchgate.net/profile/Golam_Kibria7

Laffoley D, Baxter JM (eds) (2016) Explaining ocean warming: causes, scale, effects and consequences. IUCN, Gland

Lenton A, Matear RJ, Mongin M (2018) Effects of climate change on ocean acidification relevant to the Pacific Islands. Sci Rev 2018:31–42

Mackenzei FT, Garrels RM (1966) Chemical mass balance between rivers and oceans. Am J Sci 264:507–525

Middelburg JJ, Soetaert K, Hagens M (2020) Ocean alkalinity, buffering and biogeochemical processes. Rev Geophys 58:1–28

NASA (n.d.). https://climate.nasa.gov/vital-signs/carbon-dioxide/

NIWA (n.d.). https://niwa.co.nz/coasts-and-oceans/faq/what-is-ocean-acidification

O'Boyle S (2020) Oxygen depletion in coastal waters and the open ocean. In: Arias AH, Botte SE (eds) Coastal and deep ocean pollution, 1st edn. CRC Press, Boca Raton, FL, pp 1–27. ISBN: 13: 978-1-138-56939-3

Siegenthaler U (2005) Stable carbon cycle-climate relationship during the late pleistocene. Science 310(5752):1313–1317

Sutton PJH (2018) Effects of climate change on sea temperature relevant to the Pacific Islands. Sci Rev 2018:20–30

The National Academies (2013) Ocean acidification starting with the science. The National Academies, Washington, DC. https://www.nap.edu/resource/12904/OA1.pdf

The Royal Society, US National Academy of Sciences (2020) Climate change evidence & causes. An overview from the Royal Society and the US National Academy of Sciences. The Royal Society, US National Academy of Sciences, London, Washington, DC. https://royalsociety.org/~/media/royal_society_content/policy/projects/climate-evidence-causes/climate-change-evidence-causes.pdf

Turchyn AV, DePaolo DJ (2019) Seawater chemistry through phanerozoic time. Annu Rev Earth Planet Sci 47:97–224

Turley C, Brownlee C, Findlay HS, Mangi S, Ridgwell A, Schmidt DN, Schroeder DC (2010) Ocean acidification in MCCIP annual report card 2010-11. MCCIP Sci Rev:1–27

UN (n.d.). https://www.un.org/en/climatechange/what-is-climate-change

Urey HC (1952) On the early chemical history of the earth and the origin of life. Geophysics 38:31–363

Climate Change: Impact on Fauna and Fishing Activity of River

Anirudh Kumar and Rajive Kumar Brahmchari

Abstract

The change in climatic conditions is a phenomenon both manmade and natural. Climate change not only affects human life but it has a very hazardous impact on the riverine aquatic ecosystem also. Due to the temperature rise, several hydrological parameters have been changed and developed a negative impact on aquatic life. The change is like the migration of aquatic organisms due to destruction of feeding and breeding habitat, early maturation in fish, reduction in water level, and change in the catchment area. Reduction in primary productivity is the major cause of reduction in fish stock size. Industrial waste disposal is also one of the major stressors for an aquatic ecosystem. Fishing behavior and pattern got changed in every river system due to the destruction of the feeding and breeding ground maturation period of fish. Climate change is a continuous process and in this situation introduction of genetically modified organisms, river ranching programs, and modifications in riverine fishing policy may be able to secure fisheries resources sustainably in the river system.

Keywords

Climate change · Aquatic system · Thermal regimes · Aquatic fauna · Fishing

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1 Introduction

Climate change is a very serious issue for the aquatic environment (Mohanty and Mohanty 2009; IPCC 2007). It has a huge negative impact on inland fisheries and aquaculture practices in India. In inland water bodies, riverine biomass is highly affected by climate change like increase in water temperature, reduction in the level of water in the river, changes in fish feeding and breeding ground, reduction in the availability of natural live food, reduction in fish growth, reduction in fish stock size, etc. which directly or indirectly develop impact on fishermen whose livelihood is fully dependent on the riverine catch. Fisheries are already a rapidly developing sector but due to overexploitation of riverine fisheries reduction in fish stock size is one of the major drawbacks of riverine capture fisheries. A riverine fishery faces lots of difficulties in maintaining natural sustainable conditions due to the impact of climate change.

Due to industrialization and urbanization riverine ecology is already under stress and climate change developed additional stress on the system. The growing population of a country that is settled nearby the river is fully dependent on riverine natural resources to fulfill their requirements and enhance their livelihood and is considered vulnerable due to climate change. The riverine system of India is having one of the richest diverse aquatic resources in the world. This country is having 12 major river systems with a total catchment area of 252.8 million hectares. The Ganga and Brahmaputra river system is considered as largest because it holds a 110-million-hectare catchment area.

2 Impact on Hydrology

The environment of riverine aquatic organisms is greatly influenced by a change in water temperature, and this happens due to the impact of change in climate which alters atmospheric energy and heat exchange (Caissie 2006). Climate change not only affects the atmospheric and aquatic systems but also has a huge direct impact on runoff through precipitation. The flow of rivers derives from precipitation which helps to know the water supply and the course by which precipitated water reaches the river channel (Poff et al. 1997). The catchment area of the river is also reduced due to changes in annual runoff and precipitation (Tang and Lettenmaier 2012).

The increase in water temperature by changing climate causes a decrease in discharge up to 20–40% which again gets affected by higher temperature due to reduction in water level (Van Vliet et al. 2011). The ecosystem of the river gets disturbed due to climate change because many fish species changed their habitat.

Several aquatic organisms are very much exposed to human being-induced pressure (Woodward et al. 2010). Of all the aquatic organisms fish are ectothermic. Hence, they are directly dependent on the atmospheric and water temperatures.

Water pollution due to industrialization is also one of the major causes of disturbance in the riverine ecosystem. Some of the fish species are lost due to changes in water quality and due to a lack of required quality habitat for feeding and breeding (Reyjol et al. 2007). Greenhouse gas emission which is initiated by activities of human beings also imparts an unpredictable change in the aquatic environment mainly to the diversity of freshwater aquatic organisms (Dudgeon et al. 2006; Woodward et al. 2010).

2.1 Water Temperature

Variation in temperature of the riverine ecosystem is one of the major concerns for the habitat of organisms (Brett 1956). Due to the ectothermic nature of fish, all life stages, i.e., from juvenile to adult, are fully dependent on their ambient temperature. According to Caissie (2006), the factors, which are responsible for the change in riverine water temperature, are:

1. Condition of atmospheric air
2. Discharge of stream
3. Land topography
4. Streambed

The condition of atmospheric air is highly responsible for the exchange of heat in the water mass of rivers. The discharge of the stream estimates the amount of water flow in the river. Generally, narrow rivers get fast affected by heating and cooling due to less amount of water in a particular area. The air temperature variation is found in different geographical areas. Streambed of rivers depends on several factors like land topography, water temperature, water pressure, etc. (Caissie 2006).

There is no linear trend found in temperature variation in the river. If the river is small and has less depth then there will be higher water temperature than larger rivers in the same geographical area (Caissie 2006). In a chemo-physical environment, water temperature plays a very significant role for an aquatic organism. Lower temperatures were observed during morning hours and higher temperatures were observed during the afternoon. Daily minimum temperatures can be observed in the morning hours and maximum temperatures in the late afternoon (Woodward et al. 2010).

2.2 Interactions of Climate Change with Other Stressors

Other than climate change non-climatic drivers also act as a stressor for the aquatic environment and organisms. The non-climatic drivers like increase in population, urbanization, emission of pollution due to industrialization, and economic upliftment affect the aquatic ecosystem (Dudgeon et al. 2006; Nelson et al. 2006).

The groundwater recharge of fresh water and increase in the chances of floods are also affected due to deforestation and urbanization. All these changes affect both agricultural and aquaculture practices (Bates et al. 2008). Thus, in the future, land availability will be a major concern for freshwater agriculture and aquaculture

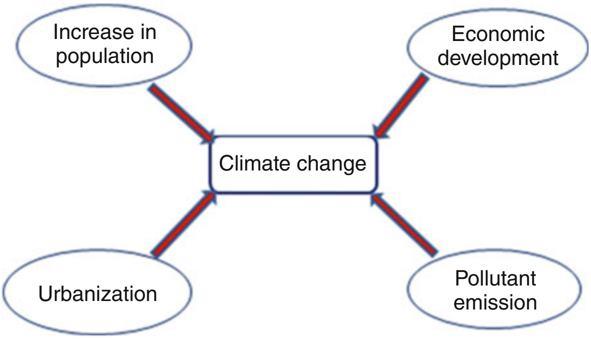

Fig. 1 Non-climatic drivers

systems. The loss of water of about 90% due to irrigation alone severely impacts freshwater availability for aquaculture, humans, and ecosystems (Fig. 1) (Döll 2009).

The human impact like the generation of hydropower also develops huge pressure on riverine ecosystems. The change in river flow may be one of the reason for chnage in stock of fish and other organisms and disturbing discharge regimes on hourly time scale (Poff and Zimmerman 2010). Due to changes in streambed and stream flow also got affected by changes in climatic conditions.

3 Ecological Impacts of Thermal Regimes on Aquatic Fauna

All the aquatic organisms including fish are affected by the temperature of the surrounding water starting from the egg to the adult stage (Brett 1956). Fry (1947) gives five main categories of effects of temperature on fish:

1. Change in metabolic and development rates
2. Effect on movement and disturbance
3. Change in movement pattern
4. Reduction in immune response
5. Fish may die

The impact of temperature on aquatic fauna occurs at different organizational levels, i.e., from individual to population or community (McCullough et al. 2009; Woodward et al. 2010). Therefore, the change in climate affects almost everything about individual fish including suitable habitat, rate of survival, breeding, hatching, feeding, physical condition, physiological condition, and metabolic activity (Fig. 2).

The temperature tolerance level of organisms will determine the adoption level in a changing environment. In this changing climatic condition, introduction of Genetically Modified Organisms (GMOs) is the only solution to overcome all these existing problems of climate change.

According to Magnuson et al. (1997), aquatic organisms can be classified into three thermal guilds:

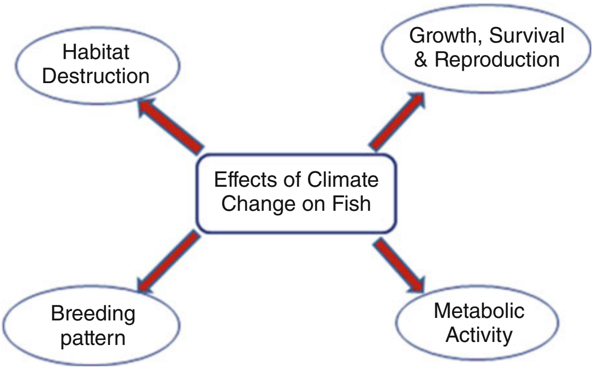

Fig. 2 Effects of climate change on fish

1. Cool-water species (<20 °C)
2. Cold-water species (20–28 °C)
3. Warm-water species (>28 °C)

The behavior of fish will get changed if their surrounding environment temperature will get changed. The fish showing the same behavior used to share the same habitat, but a due climate change has disturbed their habitat. Microhabitat has been developed for the temporary settlement of organisms in changing climatic conditions. This not only affects the aquatic fauna but also affects the fishermen and their livelihoods (McCullough et al. 2009). Due to non-climatic stressors, some aquatic organisms would migrate from their original place to other suitable places but not very far from their original habitat. Climate change has disturbed the habitat of several aquatic organisms at all levels of life stages permanently. Thermal stress is also involved in the reduction of disease resistance, changing feeding, behavior, etc.

At the higher level, several fish species' stocks have been disturbed including abundance, productivity, and genetic diversity. If this condition remains for a longer period there will be many fish species migrating to different levels, i.e., higher or lower streams. The fish species coming under endangered is also due to changes in climatic conditions (Bässler et al. 2010; Sauer et al. 2011; Dirnböck et al. 2011; Vitecek et al. 2015; Rabitsch et al. 2016). Generally, climate determines bio-geographical distribution patterns (Reyjol et al. 2007), and hence, climate change will have huge impacts on aquatic communities. Comte et al. (2013) observed distribution changes for fish due to climate.

4 Impact on Fishing

Climate change not only disturbed riverine hydrology and their fauna but also developed a negative impact on sustainable fishing practices. In general, due to the rise in surface water temperature fish stock changed. This change not only disturbed fish species availability but it also changed fish breeding time, fish habitat, growth and feeding pattern. Due to all these changes in riverine fauna fishermen faced several problems like:

1. Reduction in catch per unit effort
2. Reduction in fishing efficiency of gear
3. Loss of fish species diversity
4. Less catch with the smaller size of fish
5. More energy and time involved in fishing practice, etc.

The livelihood of most of the fishermen is fully dependent on fish caught from the river. Due to the hazardous impact of climate on riverine fisheries resource the amount of catch has been reduced and the socio-economic status of fishermen is in danger. Now, some fishermen try to move towards other occupations to fulfill the demand of their families and to enhance their livelihood. Some fishermen who are still fishing in this occupation have reduced the mesh size of the gear without bothering about the ecosystem and sustainability of resources to harvest more amount of catch per unit of catch. Due to the reduction in mesh size of gear, gear became unselective and more than 50% of catches are coming under bycatch which is now a very serious issue for the sustainability of the aquatic resource.

Due to changes in breeding behavior and patterns, fishermen also used to harvest mature fishes, i.e., brooders. Over-exploitation which includes recruitment overfishing and growth overfishing of aquatic resources is also a major concern. Sustainability of resources is very important, and it can only be possible by enhancing fish stock and reducing overfishing. It can be done by involving a river ranching program, a fishing ban period during the breeding time of fish, changes in design, and construction of gear including mesh size and netting material.

5 Conclusion

Climate change is a hidden hazardous continuous phenomenon that disturbed human and aquatic life. Besides all these, it has a huge impact on the riverine ecosystem. The major effect of climate change is a rise in the temperature of air and water. Due to the increase in riverine water temperature, several changes occurred such as destruction in feeding and breeding ground of several aquatic organisms, change in growth, survival, and maturation period, change in the food chain and food web, change in fishing pattern, and change in the sustainability of riverine fisheries resource due to increase in bycatch and overexploitation. It is not easy to mitigate the entire above-listed problems raised due to change in climate, but we can maintain the riverine fisheries resource sustainable by the introduction of a river ranching program and modifications in fishing policy like mesh size regulation of gears, fishing quota, fishing ban period, etc. Besides all these, the introduction of Genetically Modified Organisms (GMOs) which can sustain climate change stressors in riverine conditions can make fisheries resource sustainable.

References

Bässler C, Müller J, Hothorn T, Kneib T, Badeck F, Dziock F (2010) Estimation of the extinction risk for high-montane species as a consequence of global warming and assessment of their suitability as cross-taxon indicators. Ecol Indic 10:341–352

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (eds) (2008) Climate change and water. Technical paper of the intergovernmental panel on climate change. IPCC Secretariat, Geneva, p 210

Brett JR (1956) Some principles in the thermal requirements of fishes. Q Rev Biol 31:75–87

Caissie D (2006) The thermal regime of rivers: a review. Freshw Biol 51:1389–1406

Comte L, Buisson L, Daufresne M, Grenouillet G (2013) Climate-induced changes in the distribution of freshwater fish: observed and predicted trends. Freshw Biol 58:625–639

Dirnböck T, Essl F, Rabitsch W (2011) Disproportional risk for habitat loss of high-altitude endemic species under climate change. Glob Chang Biol 17:990–996

Döll P (2009) Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. Environ Res Lett 4:1–13

Dudgeon D, Arthington A, Gessner M, Kawabata Z-I, Knowler D, Lévêque C, Naiman R, Prieur-Richard A-H, Soto D, Stiassny M, Sullivan C (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. Biol Rev Camb Philos Soc 81:163–182

Fry FEJ (1947) Effects of the environment on animal activity. Publications of the Ontario fisheries research. Laboratory 55:1–62

IPCC (2007) Fourth assessment report - climate change 2007: synthesis report. IPCC, Geneva

Magnuson JJ, Webster KE, Assel RA, Bowser CJ, Dillon PJ, Eaton JG, Evans HE, Fee EJ, Hall RI, Mortsch LR, Schindler DW, Quinn FH (1997) Potential effects of climate changes on aquatic systems: laurentian great lakes and precambrian shield area. Hydrol Process 11:825–871

McCullough DA, Bartholow JM, Jager HI, Beschta RL, Cheslak EF, Deas ML, Ebersole JL, Foott JS, Johnson SL, Marine KR, Mesa MG, Petersen JH, Souchon Y, Tiffan KF, Wurtsbaugh WA (2009) Research in thermal biology: burning questions for Coldwater stream fishes. Rev Fish Sci 17:90–115

Mohanty S, Mohanty BP (2009) Global climate change: a cause of concern. Natl Acad Sci Lett 32: 149–156

Nelson GC, Bennett E, Berhe AA, Cassman K, DeFries R, Dietz T, Dobermann A, Dobson A, Janetos A, Levy M, Marco D, Nakicenovic N, O'Neill B, Norgaard R, Petschel-Held G, Ojima D, Pingali P, Watson R, Zurek M (2006) Anthropogenic drivers of ecosystem change: an overview. Ecol Soc 11:29

Poff NL, Zimmerman JKH (2010) Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshw Biol 55:194–205

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC (1997) The natural flow regime: a paradigm for river conservation and restoration. Bioscience 47:769–784

Rabitsch W, Graf W, Huemer P, Kahlen M, Komposch C, Paill W, Reischütz A, Reischütz PL, Moser D, Essl F (2016) Biogeography and ecology of endemic invertebrate species in Austria: a cross-taxa analysis. Basic Appl Ecol 17(2):95–105

Reyjol Y, Hugueny B, Pont D, Bianco PG, Beier U, Caiola N, Casals F, Cowx IG, Economou A, Ferreira MT, Haidvogl G, Noble R, de Sostoa A, Vigneron T, Virbickas T (2007) Patterns in species richness and endemism of European freshwater fish. Glob Ecol Biogeogr 16:65–75

Sauer J, Domisch S, Nowak C, Haase P (2011) Low mountain ranges: summit traps for montane freshwater species under climate change. Biodivers Conserv 20:3133–3146

Tang Q, Lettenmaier DP (2012) 21st century runoff sensitivities of major Global River basins. Geophys Res Lett 39:1–5

Van Vliet MTH, Ludwig F, Zwolsman JJG, Weedon GP, Kabat P (2011) Global river temperatures and sensitivity to atmospheric warming and changes in river flow. Water Resour Res 47: W02544

Vitecek S, Graf W, Previšić A, Kučinić M, Oláh J, Bálint M, Keresztes L, Pauls SU, Waringer J (2015) A hairy case: the evolution of filtering carnivorous Drusinae (Limnephilidae, Trichoptera). Mol Phylogenet Evol 93:249–260

Woodward G, Perkins DM, Brown LE (2010) Climate change and freshwater ecosystems: impacts across multiple levels of organization. Philos Trans R Soc Lond Ser B Biol Sci 365:2093–2106

Possible Impact of Climate Change on Fisheries

Adita Sharma, Viabhav Kumar Upadhayay, and Tanushri Ghorai

Abstract

The impact of climate change on fisheries has climbed to the top of the priority list in recent years because of its direct and potential implications on the environment and human society, notably food security. Everything from the cellular level to the ecological level is affected by climate change. In terms of water resources, biological variety, productivity, and sustainability, climate change has the potential to have a significant impact on fisheries. Aquaculture operations are projected to be influenced in terms of production and agricultural methods, in addition to profitability. Although this occurrence is unavoidable, certain mitigation methods and management techniques can help to mitigate negative consequences and build resilience in the face of adversity. Individuals, businesses, governments, and regulatory bodies all have a role to play in reducing the likelihood of future bad effects. Climate change mitigation should be planned and implemented with full awareness of this complexity.

Keywords

Climate change · Fisheries · Coastal habitat · Metabolic stress and sustainable development

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1 Introduction

Natural climate variability and human-induced climate change, especially more frequent and intense extreme events, have broad negative impacts and linked losses and damages to nature and humans. The vulnerability has been lessened as a result of some development and adaptation measures. The most vulnerable people and systems have been seen to be disproportionately affected across sectors and locations. The increase in weather and climatic extremes has resulted in some permanent consequences, including natural and human systems being pushed to the limit of their adaptability (Pörtner et al. 2022).

The warming of the climate system is unambiguous. The atmosphere and oceans have warmed, the amount of snow and ice has decreased, and the location of the oceans has increased. As a result, the observed warming since the mid-twentieth century has likely been caused primarily by mortal impact. The ocean has absorbed 93% of the clean heat and 30% of the human CO_2 emissions. Between 1901 and 2010, the global mean ocean position increased by 0.19 m (IPCC 2022). As a result of global warming, submarine systems that support fisheries and monoculture are undergoing substantial changes, and protrusions suggest that these changes will be exacerbated in the future (Barange et al. 2018). To demonstrate and project future environments, a variety of barometrical groupings of GHGs are used; the majority of these situations show that an enormous portion of anthropogenic environmental change is irreversible into the indefinite future, even after the complete suspension of anthropogenic CO_2 discharges (FAO 2018).

Environmental change is influencing precipitation and liquefaction of snow and ice in many places, changing hydrological frameworks, and impacting water assets in terms of quantity and quality. Precipitation is expected to increase in the central regions while decreasing elsewhere, according to projections. The temperature of water bodies is rising over the world, resulting in more articulated stratification of the water column, with more sensational repercussions for freshwater systems than for seas due to their shallowness and lower buffering limit (Moustahfid et al. 2018). Increased temperature lowers dissolved oxygen levels, and oxygen least zones in the waters have expanded over the last several years, both on the beach and further out. This pattern is meant to continue. Upwelling patterns, such as the Gulf Stream and the California Current, are weakening, while upwelling in other locations, such as the Canary, Humboldt, and Benguela Current systems, is expanding. As of yet, reactions are mixed, and expectations are uncertain. Water acidification is caused by the waters' assimilation of increasing levels of anthropogenic CO_2, which may impede shell-framing amphibian life. Water acidity has increased by 26% since the modern upheaval, and this trend will continue, especially in hotter low and mid-latitudes (Harrod et al. 2018). Primary production in the seas is expected to decline by 3% to 9% by 2100; observations in freshwater systems vary depending on the area, but estimates for both marine and freshwater systems are highly speculative because primary production is an integrator of changes in light, temperature, and supplements (Bahri et al. 2018).

2 Climate Change: Present Scenario

According to the Intergovernmental Panel on Climate Change (IPCC 2022), global greenhouse gas substance discharges averaged their highest levels in human history from 2010 to 2019; however, the rate of growth has moderated. Limiting a severe atmospheric variation to 1.5 °C is impossible without rapid and dramatic discharge decreases in all locations. Since roughly 2010, there have been documented cost reductions of up to 85% in solar and wind energy, as well as batteries. A growing number of laws and regulations have improved energy productivity, slowed deforestation, and accelerated the deployment of sustainable power. Limiting global warming would necessitate significant changes in the electrical sector. Major reductions in fossil gasoline usage, significant electrification, advanced electricity efficiency, and the use of alternative fuels will all be part of this plan (inclusive of hydrogen). Having the right laws, infrastructure, and generation in place in the region to allow for changes in our lives and behavior can result in a 40–70% reduction in greenhouse gas emissions by 2050 (Jaiswal et al. 2019). The evidence also suggests that making these lifestyle changes can improve our fitness and well-being. Cities and diverse urban locations also provide a plethora of emission-reduction opportunities. Reduced energy use, electrification of distribution in combination, and improved carbon uptake and storage can help achieve these goals.

Established, rapidly developing, and emerging cities all have options. Using materials more efficiently, reusing and recycling products, and limiting trash are all ways to reduce emissions in the workplace. Low- to zero-greenhouse gas production methods are at the pilot to the near-commercial stage for essential components such as steel, constructing materials, and chemicals. This quarter accounts for almost a quarter of global emissions. It may be challenging to achieve net zero, and it may necessitate innovative industrial techniques, low- and zero-emission electricity, hydrogen, and, if necessary, carbon sequestration and storage. Agriculture, forestry, and other land uses can reduce emissions on a huge scale while also deferring and saving carbon dioxide. Land, on the other hand, cannot make up for the fact that carbon reductions in many industries were not achieved on time. Response options can benefit biodiversity, help us adapt to climate change, and provide secure livelihoods, food and water sources, and timber supply (Pratap et al. 2019).

3 Observations in Climate Change

Height-based warming is observed in the excessive mountain system. In 2016 and 2018, Asia suffered extreme heat, which, according to an event attribution study, would have been unmanageable without anthropogenic global warming (Imada et al. 2018). If fish continue to live in warm bodies of water, their growth will be slowed and their maximum size will be limited by their increased metabolic rate. Climate change is expected to affect primary output at lower latitudes, where the bulk of small-scale fisheries is found, and lowering fisheries productivity.

4 Impacts of Climate Change on Coastal Habitat

Weather change, as well as rising temperatures, ocean acidification, and sea-level rise, have negative consequences for the services and livelihoods of those who rely on them in Asia’s coastal regions. Coral reef bleaching levels varied depending on the presence of stress-tolerant symbiotic species and higher heat thresholds. Coral reefs, tidal marshes, seagrass meadows, plankton communities, and other marine and coastal ecosystems are at risk of irreversible loss as a result of global warming, especially if temperatures rise to 2 °C or higher. Pollution, aquaculture conversion, agriculture, weather-related hazards like SLR (Sea Level Rise), and coastal floods continue to be difficulties for mangroves in the region. Glaciers provide water to around 220 million people in Asia’s downstream regions. Between 1998 and 2007, the amount of glacier meltwater flowing across the southern Tibetan Plateau increased, and this trend is expected to continue until 2050 (Poulain et al. 2018).

Flooding is expected to result in considerable increases in annual financial losses in coastal communities, primarily in South and Southeast Asia, between 2005 and 2050, with extremely high losses in East Asian cities under an excessive emission scenario. Weather extrude will raise the urban heat island impact in Asian towns by 1.5 °C and 2 °C, respectively, when the temperature rises by 1.5 °C and 2 °C Guldberg et al. (2018). Nearly all cities will suffer increased hazards from high temperatures and precipitation under the excessive-emission scenario, affecting freshwater availability, regional food security, human health, and industrial outputs.

5 Positive Impact on Fisheries

Reduced dry season flow rates in rivers and basins are expected to result in poorer fish yields due to effects on spawning and larval dispersal. Pelagic fish productivity in the Indian Ocean may increase as a result of climate change. Increased wind speed stirs up deep water, forcing nutrients to ascend to the surface and boost phytoplankton production. Pelagic production should improve if food is available at the base of the food system (FAO 2020). Pelagic stock increases, on the other hand, may not benefit small-scale fishers if they occur in deeper oceans beyond their reach.

The effect of increasing temperatures on rainbow trout was studied by researchers (*Oncorhynchus mykiss*). In the winter, a 2 °C rise in temperature boosted their hunger, growth, protein synthesis, and oxygen consumption; in the summer, the same rise had the opposite effect. Metabolic costs are increased when temperature interacts with dropping pH, and rising nitrogen and ammonia levels (Maulu et al. 2021).

6 The Effects of Metabolic Stress

Using a combination of experimental and subject studies, the physiological repercussions and impacts on mortality of ray-finned fish, eelpout (*Zoarces viviparus*), in the southern North Sea were linked to thermally constrained oxygen shipping during summer warm spells. For a few weeks in the summer of 2004, temperatures in the Fraser River, Canada, exceeded levels previously recorded in a 60-year time series, resulting in enhanced salmon mortality. These examples indicate that weather variations can occur over short periods within a year and can thus be linked to changes in the frequency and severity of severe occurrences (droughts, floods, heat waves, and storms), as well as changes in mean values (Soto et al. 2018).

7 Other Impacts

Increased frequency of violent climate events can potentially risk fisherman's safety, inflict damage to dwellings, services, and infrastructure, particularly in coastal locations, and disrupt many coastal ecosystems (Nicholls et al. 2007). Flooding will become more likely as intense rainfall events become more often, degrading water quality and putting physical infrastructure in danger. As temperatures rise, key infrastructures such as electric lines, street and rail transportation, and developed infrastructure such as airports and harbors are more vulnerable to weather-related disasters, particularly in coastal locations.

Infrastructure adaptation (such as flood safety measures and weather-resistant highways and power infrastructure); institutional adaptation (sustainable land use planning, zoning plans); six environment-based solutions (mangrove restoration, restoring and managing urban green spaces, urban farming); technological developments (smart cities, early warning systems); and behavioral adaptation are all examples of urban adaptation (e.g., preparedness measures, improved awareness).

8 Future Predictions

According to the scenarios, limiting global warming to 1.5 °C (2.7 °F) will necessitate a peak in greenhouse gas emissions by 2025 at the latest, and a 43% drop in emissions by 2030; at the same time, methane emissions may need to be reduced by a third.

While carbon dioxide emissions reach net zero, the global temperature will steady. This suggests achieving net-zero carbon dioxide emissions globally in the early 2050s for 1.5 °C (2.7 °F) and miles in the early 2070s for 2 °C (3.6 °F). According to this analysis, limiting global warming to 2 °C (3.6 °F) still necessitates a peak in global greenhouse gas emissions by 2025 at the latest, and quarter reductions by 2030 (Dhara and Koll 2022).

8.1 Closing Investment Gaps

The record appears to be independent of technology, demonstrating that, while economic flows are 3–6 times lower than those required by 2030 to keep global warming at 2 °C (3.6 °F), there may be sufficient global capital and liquidity to close investment gaps. It is, however, based on clear signals from governments and the international community, including a stronger convergence of public finance and policy.

In 2050, if we take the efforts necessary to restrict warming to 2 °C (3.6 °F) or less, global Gross Domestic Product (GDP) would be only a few percentage points lower than if we maintain current policies, notwithstanding the monetary benefits of decreased adaptation costs and avoided weather impacts (Garg et al. 2015).

9 Steps for Sustainable Development Goals

Long-term development requires more swift and equitable climate action in terms of mitigating and adapting to climate change repercussions. Some response options can absorb and store carbon while simultaneously supporting communities in mitigating climate change's effects. Parks and open spaces, wetlands, and urban agriculture, for example, can all contribute to reducing flood risk and heat island effects in cities. Mitigation of industry can help to reduce environmental impacts while simultaneously increasing jobs and commercial opportunities. Renewable energy and reforms in public transportation can all promote health, employment, and equity. Climate change is the result of more than a century of unsustainable energy and land use, lifestyles, and consumption and production patterns.

10 Conclusion

Climate change will have a substantial impact on aquaculture and fisheries. These are projected to have a negative influence on low-latitude fisheries, resulting in damage to critical ecosystems such as coral reefs and mangroves, as well as fish population reductions as a result of increased water temperatures and lower primary productivity. Extreme weather events in both inland and coastal systems will almost certainly have a significant impact on future fisheries production. Reduced fishing mortality in the majority of fisheries, which are either fully fished or overexploited, is the most viable option for limiting climate change implications.

References

Bahri T, Barange M, Moustahfid H (2018) Climate change and aquatic systems. In: Impacts of climate change on fisheries and aquaculture. FAO Fisheries and Aquaculture technical paper, 627, ISSN 2070-7010

Barange M, Bahri T, Beveridge MCM, Cochrane KL, Funge-Smith S, Poulain F (eds) (2018) Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper No. 627. FAO, Rome, 628 pp

Dhara C, Koll RM (2022) How and why India's climate will change in the coming decades. The India Forum, June 2022

FAO (2018) Impacts of climate change on fisheries and aquaculture. Synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture technical paper, 627

FAO (2020) The state of world fisheries and aquaculture (2020). Sustainability in action. Rome. https://doi.org/10.4060/ca9229en

Garg A, Mishra V, Dholakia H (2015) Climate change and India: adaptation gap (2015) - a preliminary assessment. Working paper of Indian Institute of Management Ahmedabad (IIMA) W.P. No. 2015-11-01

Guldberg OH, Jacob D, Taylor M, Bindi M, Brown S, Camilloni I, Diedhiou A, Djalante R, Ebi KL, Engelbrecht F, Guiot J, Hijioka Y, Mehrotra S, Payne A, Seneviratne SI, Thomas A, Warren R, Zhou G (2018) Impacts of 1.5°C global warming on natural and human systems. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways

Harrod, C, Ramírez, A, Jorgensen, JV, Simon Funge-Smith SF (2018) How climate change impacts inland fisheries. FAO Fisheries and Aquaculture technical paper, 627, ISSN 2070-7010

Imada Y, Watanabe M, Kawase H, Shiogama H, Arai M (2018) High temperature event in Japan could not have happened without human-induced global warming. SOLA, 2019 15A:8–12. https://doi.org/10.2151/sola.15A-002

IPCC (2022) IPCC sixth assessment report impact. Adaption and vulnerability. https://www.ipcc.ch/report/ar6/wg2

Jaiswal A, Joshi M, Kwatra S (2019) Climate consequences: if India sneezes Jindal. Global Law Rev. https://doi.org/10.1007/s41020-019-00089-y

Maulu S, Hasimuna OJ, Haambiya LH, Monde C, Musuka CG, Makorwa TH, Munganga BP, Phiri KJ, Nsekanabo JD (2021) Climate change effects on aquaculture production: sustainability implications, mitigation, and adaptations. Front Sustain Food Syst 12:609097. https://doi.org/10.3389/fsufs.2021.609097

Moustahfid H, Marsac F, Gangopadhyay A (2018) Climate change impacts, vulnerabilities and adaptations: Western Indian Ocean marine fisheries. FAO Fisheries and Aquaculture technical paper, 627, ISSN 2070-7010

Nicholls RJ, Wong PP, Burkett VR, Codignotto JO, Hay JE, McLean RF, Ragoonaden S, Woodroffe CD (2007) Coastal systems and low-lying areas. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 315–356

Pörtner HO, Roberts DC, Poloczanska ES, Mintenbeck K, Tignor M, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A (2022) IPCC: summary for policymakers. In: Climate change 2022: impacts, adaptation, and vulnerability. Cambridge University Press

Poulain F, Cornell AH, Shelton C (2018) Methods and tools for climate change adaptation in fisheries and aquaculture, FAO Fisheries and Aquaculture technical paper, 535, ISSN 2070-7010

Pratap B, Sharma P, Patel L, Singh AT, Gaddam VK, Oulkar S, Thamban M (2019) Reconciling high glacier surface melting in summer with air temperature in the semi-arid zone of Western Himalaya. Water 11:1561. https://doi.org/10.3390/w11081561

Soto D, Ross LG, Handisyde N, Bueno PB, Beveridge CM, Dabbadie L, Manjarrez JA, Cai J, Pongthanapanich T (2018) Climate change and aquaculture: vulnerability and adaptation options. FAO Fisheries and Aquaculture technical paper, 535, ISSN 2070-7010

Impact of Global Warming on Changing Pattern of Biodiversity and Fish Production in Inland Open Waters

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Abstract

Climate change rapidly transforms aquatic ecosystems globally, but the impact of changes in tropical wetlands is not well documented. Sustainable freshwater biodiversity and fisheries management require keeping a record of ongoing and historical stressors such as increased global temperature and fishing pressure. This task is more complicated in tropical water bodies, including India, where publications on the ecosystem change are minimal, and the fishers mostly do subsistence fishing and farming for livelihood and nutrition. Here, we describe the impacts of climate change on fisheries, freshwater ecosystems, aquatic biodiversity, adaptation, and mitigation strategies. The present chapter is divided into two parts; the first part discusses the causes and concerns of global warming, and the second part deals with the impacts of global warming on freshwater fisheries and their biodiversity, suggestive measures, and the development of monitoring methods.

Keywords

Global warming · Aquatic biodiversity · Fisheries · Rivers

1 Introduction

The term “climate” refers to the long-term weather pattern in a particular area, whereas “Weather” refers to daily or weekly changes in the atmosphere. Climate is generally described in years, decades, centuries, and millennia. Nowadays, climate change commonly represents any change over a more extended period, like a few

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decades or centuries. Climate change may be due to natural causes or because of the activities of humans. Climate change can change or alter the entire ecosystem, including the biota. The global environment, aquatic biodiversity, and sustainable development of climate change have increased and intensely threatened the global environment, aquatic biodiversity, and sustainable human development by altering thermal regimes (Huang et al. 2021).

Many factors can cause a warming of our climate, for example, more energy from the Sun and thus the increased greenhouse effect. Greenhouse gases, such as water vapor, carbon dioxide, and methane, occur naturally in the atmosphere. However, human activities have also directly increased the concentration of carbon dioxide, methane, and other greenhouse gases in the environment. In addition to biodiversity and aquatic productivity, they provide various services for human populations, including water for irrigation, drinking and recreational activities, and a habitat for aquatic life (Verma 2016, 2017).

As the temperature rises, region-specific climates, such as erratic monsoons, severe droughts in many regions, sea-level rises, and crops are affected. Additionally, snowpack over mountains reducing and shrinking glaciers causes less melting of snowpack that flows into rivers, reservoirs, lakes, and connected wetlands for aquatic life and thus less water available for drinking, domestic use, and irrigation purposes. Higher temperatures in the climate also increased the evaporation rates, which leads to erratic rainfall and snowfall in many areas (Verma 2019).

Climate change can influence fisheries production by directly impacting primary productivity, secondary productivity, interactions in the food web, and target species' distributions and life history. Moreover, the changes in primary and secondary production follow the changes in the physical and chemical environment (Sarmiento et al. 2004), and the availability of the direct output also influences changes in the food web.

2 Cause and Concerns of Global Warming

Climate change is the changes and variations in the earth's global climate or regional environments over time. This change involves the variability in the average state of the atmosphere over a more extended period that can go to millions of years. The United Nations Framework Convention on Climate Change (UNFCCC) uses the term "climate change" for anthropogenic change and "climate variability" for other changes. From the data of 100 years, IPCC (2007) concluded that the average global air temperature over the earth's surface had been estimated to increase at 0.74 ± 0.18 °C. These shifts in the climate may be natural, but since the 1800s, the activities of humans have been the main reason for global climate change, mainly due to fossil fuels burning (like oil, coal, and natural gases), causing the greenhouse effects. Generating electricity and fire from fossil fuels such as oil, coal, and natural gas causes many greenhouse gas emissions. Fossil fuels are still the primary source of most electricity, and only a quarter comes from renewable sources like solar, wind, etc. Greenhouse gases also come from mining activities and other industrial processes. Deforestation also causes emissions as they store the carbon for a long time, but after cutting these trees, they release it into the environment. Destroying the forest, Climate change also limits the natural ability of forests to absorb carbon dioxide and limits nature's ability to maintain emissions out of the atmosphere regimes (Mohanty et al. 2010).

Climate change influences fisheries production through its effects on primary production, secondary production, food web interactions, distribution, and abundance of prey in the ecosystem. Changes in primary production can result in the physical and chemical environment, while the availability of primary producers also influences changes in the food web. Due to climate change, the distributions and relative abundance of fishes have been changed on local and regional scales. Climate change affects the biological processes of fishes and other aquatic organisms from the genetic to ecosystem level. Recent global warming has caused distributional shifts in some fish species along latitudinal and depth gradients (Mohanty et al. 2010).

Fish production is greatly influenced by climate change challenging to predict at ecosystem scales. Interspecific interactions, physiological preferences, habitat affinities, species identities, and histories vary among systems, and very few details make predictions. Therefore, in that case, we have to see forecasts of a few selected species at all levels, primarily where the past data and records are available sufficiently. Our limited information on the ecology of all species that contribute to fisheries production creates problems using species-specific models to predict fish production with changing climates. Many species-specific approaches are needed to develop alternative and potentially informative parallel approaches that do not require knowledge of individual species' ecology (Binzer et al. 2012). Rosenzweig (1971) coined the term "paradox of enrichment" after analyzing the effect of increased energy input due to global warming on the dynamics of a predator-prey system. He described the paradox as enrichment which drives a predator-prey system from stable equilibria into oscillations and finally into extinction when the population minima hit extinction boundaries. This is also explained as the principle of energy flux, where any process increasing energy fluxes relative to consumer loss rate will destabilize systems by shifting biomass at different trophic levels.

Many greenhouse gases, including carbon dioxide released into the atmosphere, lead to global warming. Wetlands are commonly called "Carbon sinks." These wetlands extract a significant amount of carbon from the atmosphere. It is reported that wetlands themselves store more than twice as much carbon as the world's total forest. The intensity of global climate change increases due to the release of carbon from the destruction of these wetlands. Human activities are also disturbed 25% of the wetlands on earth.

3 Climate Change and Aquatic Biodiversity

Biodiversity describes the variety and variability of life forms, including their genetic makeup and ecosystem. Life forms in an ecosystem vary in size and shape, from the simplest unicellular prokaryote to the more complex multicellular eukaryotic organisms. Each organism plays an essential role and contributes to ecosystem stability (Verma 2016).

The earth's biodiversity is dramatically affected by anthropogenic changes in ecosystems. Climate change gradually transforms biodiversity in the long term. Biological associations are also rearranged due to climate change. Sometimes this will take a longer duration and sometimes in a shorter duration also. Anthropogenic activity creates a new type of climate change that threatens the natural variability of biodiversity and accelerates biodiversity loss. Climate change has already changed the abundance and distribution of the aquatic ecosystem. It is reported that a slight change in the water temperature will change the currents that flow across the earth's surface. So, biodiversity conservation with environmental ethics is necessary for sustainable development and co-existence of plants and animals (Verma 2017, 2019). For overall biodiversity, the ecological balance is a must, which is necessary for the survival of the entire biota, including humans.

Aquatic ecosystems and biodiversity are susceptible to shipping, military activities, water pollution, and climate change, but fishing pressure is reported as the most significant threat. In some cases, subtle changes may affect the life history of the fish species. The most disturbing effects of climate change occur on aquatic ecosystems' primary and secondary production. Climate change can also cause water acidification through increased concentration of carbon dioxide in water and a decline in the pH of the water body. Acidification causes a detrimental effect on the water body.

Coral ecosystems dominate tropical intertidal and subtidal regions. This coral ecosystem supports a large population of birds, fishes, crustaceans, molluscs, turtles, and mammals. These areas are also used for breeding purposes by many species. Apart from reproduction, these reefs are also used as feeding areas, and because of that, the fishing productivity is high there. However, the stresses caused by the corals caused significant changes in the past 20 years (Bryant et al. 1998), and these changes have been linked irrefutably to periods of warmer than average sea temperature. In that case, corals are rapidly losing their cells, and the phenomenon is called Coral bleaching. In bleaching, colonies turn white from brown or blue, and their important symbionts are lost. Fishes that depend on corals for shelter, food, or settlement may feel sudden abundance changes or go extinct.

4 Climate Change and Freshwater Ecosystems

The impact of climate change on freshwater aquatic ecosystems will range from the direct effects of the rise in temperature and concentration of carbon dioxide to indirect effects through alterations in the hydrology that can cause changes in the local or global rainfall pattern and the melting of ice cover and glaciers.

The combination of habitat alteration, modified hydrology, changes in land use pattern, pollution, nutrient load, the spread of invasive species, increased levels of UV light, and a changing climate is a severe challenge to the aquatic ecosystems. The water cycle is also more vigorous in greater water surface evaporation and plant transpiration in a warmer climate. Moreover, climate change will affect freshwater ecosystems through higher temperatures and changes to their hydrological cycle.

Climate change has shown many negative implications for the biodiversity of freshwater ecosystems, including rivers, lakes, and streams. Climate change may cause the extinction of many important species around the world. Species that are geographically restricted are more prone to extinction. The earth's biodiversity is dramatically negatively changed by anthropogenic alterations of the ecosystems. Biodiversity is continually transformed due to climate change. Almost 70% of the earth's surface is covered by water. Climate change has already changed the abundance, diversity, and distribution of freshwater ecosystems. A small change in water temperature will change the water currents that flow across the earth's surface. Therefore, conservation of biodiversity with environmental ethics is necessary for sustainable development and co-existence of fauna and flora (Verma 2019). For maintaining the overall biodiversity, the ecological balance is the foremost agenda, which is necessary for the survival of the entire ecosystem, including humans, plants, and animals (Verma 2017, 2019). Therefore, biodiversity is an indication of the health of the ecosystems.

Many other related organisms in the ecosystems are also related to and linked to the detrimental impacts of climate change. Fishes are the most studied component of the freshwater ecosystem for the climate change study. Apart from that, many other components of the freshwater ecosystem like crustaceans, benthos, planktons, and periphytons have also faced the issues caused by climate change since many crustaceans and benthic organisms are non-motile and more helpful for studying climate change.

Benthic invertebrates and crustaceans—Acidification of water bodies caused by decreased pH because of higher carbon dioxide concentration. This harms crustaceans and molluscs. Their outer skeletons consist of aragonite, a common form of calcium carbonate that can dissolve in acidic water. As these molluscan and crustacean species reside most of their time on the bottom they can change the entire bottom profile, and thus the food chain is also disturbed. Oceanographic researchers point out that small crustaceans called krill that feed on phytoplankton have decreased by 80% in the past 30 years.

Aquaculture complements and increasingly adds to the supply chain and has significant links with capture fisheries, and is likely to be affected when the capture fisheries are affected.

The ecological systems which support fisheries are already known to be sensitive to climate variability. For example, in 2007, the International Panel on Climate Change (IPCC) highlighted various risks to aquatic systems from climate change, including loss of coastal wetlands, coral bleaching, and changes in the distribution and timing of freshwater flows. It acknowledged the uncertain effect of acidification of oceanic water, which is predicted to have profound impacts on marine ecosystems

(Orr et al. 2005). Similarly, fishing communities and related industries are concentrated in coastal or low-lying zones, which are increasingly at risk from rising sea levels, extreme weather events, and a wide range of human pressures (Nicholls et al. 2007). While poverty in fishing communities or other forms of marginalization reduces their ability to adapt and respond to change, increasingly globalized fish markets are creating new vulnerabilities to market disruptions that may result from climate change.

Fisheries and fisherfolk may impact in various ways due to climate change. The productivity distribution of freshwater fish stocks might be affected owing to the processes such as ocean acidification, habitat damage, changes in oceanography, disruption to precipitation, and freshwater availability (Daw et al. 2009). Climate change, particularly rising temperatures, can directly and indirectly affect global fish production. With increased global temperature, the spatial distribution of fish stocks might change due to the migration of fishes from one region to another in search of suitable conditions. Climate change will significantly affect freshwater biota's population dynamics via changes in transport processes that influence dispersals and recruitment (Barange and Perry 2009). These impacts will differ in magnitude and direction for populations within individual marine species whose geographical ranges span large gradients in latitude and temperature. The effects of increasing temperature on marine and freshwater ecosystems are already evident, with rapid poleward shifts in distributions of fish and plankton in regions such as the North-East Atlantic, where temperature change has been rapid (Brander 2007). Climate change has been implicated in mass mortalities of many aquatic species, including plants, fish, corals, and mammals (Harvell et al. 1999; Battin et al. 2007).

Climate change will impact global aquatic biodiversity; not native species will expand into regions where they previously could not reproduce and survive (Walther et al. 2009). Species composition and abundance will alter by climate change drives and likely affect ecosystems. The resources upon which the humans and aquatic organisms rely directly and indirectly through the food web have also changed in their availability, accessibility, and quality. Extreme weather events caused by climate change could result in the escape of farmed stock fishes and crustaceans and contribute to the loss of their genetic diversity, affecting biodiversity. Climate variability and change are projected to affect the physical, chemical, and biological components significantly. According to a study conducted by Prowse et al. (2009), the northward migration of species and the disruption and competition from invading species are already occurring and will continue to affect marine, terrestrial, and freshwater communities. This will have implications for protecting and managing wildlife, fish, fisheries resources; protected areas; and forests. Shifting environmental conditions will likely introduce new animal-transmitted diseases and redistribute some existing diseases, affecting critical economic resources and human populations. Stress on populations of iconic wildlife species, such as the polar bear, ringed seals, and whales, will continue due to changes in critical sea-ice habitat interactions. Where these stresses affect economically and culturally important species, they will significantly affect people and regional economies. Further integrated, field-based monitoring and research programs and the development of predictive models are required to allow for more detailed and comprehensive projections of change to be made and to inform the development and implementation of appropriate adaptation, wildlife, and habitat conservation and protection strategies.

Fisheries will also be exposed to a diverse range of direct and indirect climate impacts, including displacement and migration of human populations; impacts on coastal communities and infrastructure due to sea-level rise; and changes in the frequency, distribution, or intensity of tropical storms. Freshwater fisheries ecology is profoundly affected by changes in precipitation and run-off due to climate change. For example, Southern African lake fisheries will likely be heavily impacted by reduced lake levels and catches. The various impact mechanisms, complex interactions between social, ecological, and economic systems, and the possibility of sudden and surprising changes make future effects of climate change on fisheries challenging to predict. Understanding the ecological impacts of climate change is a crucial challenge of the twenty-first century. There is an evident lack of general rules regarding the impacts of global warming on biota. A study by Daufresne et al. (2009) provided evidence that reduced body size is the third universal ecological response to global warming in aquatic systems besides the shift of species ranges toward higher altitudes and latitudes and the seasonal shifts in life cycle events. Apart from fisheries, global primary production, which is related to global fisheries catches at the scale of Large Marine Ecosystems, appears to be declining, partly due to climate variability and change, with consequences for the near future fisheries catches (Chassot et al. 2010).

Other climatic change impacts on fisheries include surface winds, high CO_2 levels, and variability in precipitations. While surface wind would alter both the delivery of nutrients into the photic zone and the strength and distribution of ocean currents, higher CO_2 levels can change the ocean acidity, and variability in precipitation would affect sea levels. The global average sea level has been rising at an average rate of 1.8 mm per year since 1961, and there is evidence of increased variability in sea level in recent decades. Recently, ocean temperature and associated sea-level increases between 1961 and 2003 were 50% larger than the 2007 IPCC Report estimated. All coastal ecosystems are vulnerable to sea-level rise and more direct anthropogenic impacts. Sea-level rise may reduce intertidal habitat areas in ecologically essential regions, thus affecting fish and fisheries.

In the last few decades, the climate of the Indian subcontinent has shown observable changes, where the average annual temperature has risen remarkably. In India, observed changes include rising air temperature, frequent droughts, irrational rainfall patterns, and a regional increase in severe storm incidences in many coastal and landlocked states (Vass et al. 2009). In many states of India, the average minimum and maximum temperatures have increased by 0.1–0.9 °C. The average precipitation has decreased, and the monsoon is also delayed; climate change impacts the freshwater ecosystem's temperature and the aquatic fauna's breeding behavior. It is well known that temperature is an essential factor that strongly influences the reproductive cycle in fishes. Temperature, along with rainfall and photoperiod, stimulates fish endocrine glands, which help in the maturation of the gonads. In India, the inland aquaculture is centered on the Indian major carps, *Catla catla*, *Labeo rohita,* and *Cirrhinus mrigala*, and their spawning occurs during the monsoon (June–July) and extends till September. In recent years the phenomenon of IMC maturing and spawning as early as March has been observed, making it possible to breed them twice a year. Thus, there is an extended breeding activity compared to a couple of decades ago (Dey et al. 2007), which appears to be a positive impact of the climate change regime.

Ganga is the most extensive river system in India, with a total length of 2525 km from source to mouth; it provides water and livelihood to millions of people in the river basin. For many ecological studies, the river basin is divided into three main stretches consisting of the upper (Tehri to Kanauji) and middle (Kanpur to Patna), and lower (Sultanpur to Katwa). The analysis of 30 years' time series data on river Ganga and its connected water bodies (Vass et al. 2009) reported an increase in annual mean minimum water temperature in the upper cold-water stretch of the river (Haridwar) by 1.5 °C (from 13 °C during 1970–86 to 14.5 °C during 1987–2003) and by 0.2–1.6 °C in the aquaculture farms in the lower stretches of the river Ganga. This change in temperature regime has resulted in a noticeable biogeographical distribution of the many fish fauna. Many species that were never reported from the upper stretch of the river and were predominantly reported in the lower and middle stretches in the 1950s (Menon 1954) have now been recorded from the upper cold-water region. Among them, *Mastacembelus armatus* has been reported to be available at Tehri-Rishikesh, *Glossogobius giuris* in the Haridwar stretch, and *Xenentodon cancila* has also been reported in the cold-water stretch (Vass et al. 2009). The predator-prey ratio in the middle stretch of the river has been reported to be declined from 1:4.2 to 1:1.4 in the last three decades. Fish production has been shown to have a distinct change in the last two decades, where the contribution from IMCs has decreased from 41.4% to 8.3%, and that from catfishes and various species increased (Vass et al. 2009).

5 Climate Change Impact on Fishing and Aquaculture

Evidence of changing climate is reported in many parts of the world. Australia also reported some unique observations related to climate change. FRDC (Fisheries Research and Development Corporation) Australia reported the impact of climate change in Australian waters. They stated that climate change is responsible for symptoms like increasing intensity, frequency, and duration of extreme climate events (ECE), including floods, drought, heatwave, and bushfires (www.frdc.com.au).

5.1 Observed Changes in Temperature

Australia's climate has warmed on average by 1.44 ± 0.24 °C since national records began in 1910. Most warming has occurred since 1950, with every decade since then being warmer than before. This warming trend has increased the frequency of extreme heat events (Babcock et al. 2019). The Southeast region of Australia has been identified as a global hotspot for ocean warming, with a rate of change faster than in 90 percent of the world's oceans (Hobday and Pecl 2014).

5.2 Observed Changes in Water Chemistry

Atmospheric carbon dioxide (CO_2) levels are steadily increasing. The present atmospheric CO_2 concentration has not been exceeded during the past 420,000 years, and likely not during the past 20 million years.

The impacts of ocean acidification are uncertain but may include changes to species growth, physiology and reproduction, species composition, food web structure, nutrient availability, and calcification rates for species that produce shells and exoskeletons from calcium carbonate (Pecl et al. 2014).

5.3 Changes in Rainfall Patterns

Freshwater river systems, already subject to multiple stressors, are highly exposed to climate-related impacts, particularly changes in rainfall patterns. There is a possibility that fishes inhabiting these areas may have behavioral and/or physiological adaptations to withstand extremes to some point. Conversely, recent evidence also suggests that increasingly marginal conditions in many freshwater systems are likely to favor introduced European Carp, a hardy generalist with greater tolerance for poor water quality than most native species.

6 Adaptation and Mitigation Options

The climate change literature defines adaptation to climate change as an adjustment in ecological, social, or economic systems in response to observed or expected changes in climatic stimuli and their effects and impacts to alleviate adverse impacts of change. Adaptation is an active set of strategies and actions people take in response to or anticipating the change to enhance or maintain their well-being. Hence adaptation is a continuous stream of activities, actions, decisions, and attitudes that informs decisions about all aspects of life and reflects existing social norms and processes (Daw et al. 2009). Most capture fisheries and their supporting ecosystems are poorly managed, and the economic losses due to overfishing, habitat loss, and pollution are estimated to exceed $50 billion per year (Kelleher et al. 2009). The capacity to adapt to climate change is determined partly by material resources and networks, technologies, and appropriate governance structures. Improved governance, innovative techniques, and more responsible practices can generate increased and sustainable benefits from fisheries. There is a wide range of potential adaptation options for fisheries. To build suppleness to the effects of climate change and derive sustainable benefits, fisheries and aquaculture managers must adopt and adhere to best practices such as those described in the FAO “Code of Conduct for Responsible Fisheries,” reducing overfishing and rebuilding fish stocks. These practices must be integrated more effectively with managing river basins, watersheds, and coastal zones. Fisheries and aquaculture need to be intermingled into National Climate Change Adaptation Strategies. Without careful planning, aquatic ecosystems fisheries can suffer from adaptation measures applied by other sectors, such as increased application of dams and hydropower in catchments with high rainfall or the construction of artificial coastal defenses. Mitigation solutions to reducing the carbon footprint of Fisheries and Aquaculture will require innovative approaches. Exploration approaches include finding innovative but environmentally safe ways to sequester carbon in aquatic ecosystems and developing low-carbon aquaculture production systems. Therefore, this is interesting to exploit the importance of herbivorous fishes as a tool to help ecosystems recuperate from climate change impacts. The culture of herbivorous species can provide nutritious food with a large carbon footprint. This approach might be particularly suitable for recovering coral reefs, which are acutely threatened by climate change. The surveys of ten sites inside and outside a Bahamian marine reserve over 2.5 years demonstrated that increases in coral area, including adjustments for the initial size corals distribution, were significantly higher at reserve sites than those of non-reserve sites: the macroalgal cover was highly negatively correlated with the change in total coral over the time. Reducing herbivore use as part of an ecosystem-based management strategy for coral reefs appears to be justified (Mumby and Harborne 2010). Furthermore, farming shellfish, such as oysters and mussels, is good business and helps clean coastal water, while culturing aquatic plants helps remove waste from polluted water. The depletion of fishery resources is mainly due to anthropogenic factors such as overfishing, habitat destruction, pollution, invasive species introduction, and climate change. The most effective ways to reverse this downward trend and restore fishery resources are to promote fishery conservation, establish marine protected areas, adopt ecosystem-based management, and implement a “precautionary principle,” additionally, enhancing public awareness of biodiversity conservation, including eco-labeling, fishery ban or enclosure, and conserved forest areas (Shao 2009). The Fourth International Panel on Climate Change assessment report confirms that global warming strongly affects biological systems and that 20–30% of species risk extinction from projected future increases in temperature. One of the overall management strategies taken to conserve individual species and their constituent populations against climate-mediated declines has been the release of captive-bred animals to the wild to augment wild populations for many species. Using a regression model based on a 37-year study of wild and sea ranched Atlantic salmon (*Salmo salar*) spawning together in the wild, McGinnity et al. (2009) showed that the escape of captive-bred animals into the wild can substantially depress recruitment and, more specifically, disrupt the capacity of natural populations to adapt to higher winter water temperatures associated with climate variability, thus increasing the risk of extinction for the studied population within 20 generations. According to them, positive outcomes to climate change are possible if captive-bred animals are prevented from breeding in the wild. Rather than imposing an additional genetic load on wild populations by releasing maladapted captive-bred animals, they propose that conservation efforts focus on optimizing conditions for adaptation by reducing exploitation and protecting critical habitats.

7 Conclusion

The changes in the climate have a massive impact on biodiversity. Factors such as rising sea levels and increasing global temperature hugely impact freshwater and marine ecosystems. This causes the extinction of many species. Because of climate change, many species have been declared vulnerable and extinct. IUCN (International Union for Conservation of Nature and natural resources) released red book data on the present status of many species as Extinct, Extinct in the wild, Vulnerable, Least concerned, etc. Factors such as deforestation, construction, large-scale development like dams and other big developmental projects, clearing of forest land for agriculture, and other non-agricultural uses have significantly impacted the ecosystem's biodiversity. In the present time, the protection of biodiversity has become very crucial. It is therefore essential to know and understand the negative and positive impacts of climate change on freshwater biodiversity, and possible mitigation strategies should be undertaken to control adverse effects of climatic change on aquatic biodiversity. Conservation of biodiversity is the planning and sustainable management of biological resources to maintain the continuous supply, quality, value, and diversity of aquatic life. There is an urgent need to control the emissions of greenhouse gases directly into the environment. Strict rules and regulations are needed to control greenhouse gases in the environment properly. Not only can the legislative parts control climate change, but people should be encouraged and understand the destructive impacts of climate change. We should think of some alternatives to these greenhouse gases. Maybe the electrification of the vehicle will help in the control of the climate change impacts. The enforcement of laws only cannot bring about biodiversity conservation. An alternative energy source and its judicial use can be helpful for the set target. A time should be drafted to overcome the issue in the proper time frame.

References

Babcock RC et al (2019) Severe continental-scale impacts of climate change are happening now: extreme climate events impact marine habitat forming communities along 45% of Australia's coast. Front Mar Sci:411

Barange M, Perry RI (2009) Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture. In: Cochrane K, De Young C, Soto D et al (eds) Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. Food and Agriculture Organization, Rome, pp 7–106

Battin J, Wiley MW, Ruckelshaus MH, Palmer RN, Korb E, Bartz KK, Imaki H (2007) Projected impacts of climate change on salmon habitat restoration. Proc Natl Acad Sci 104(16): 6720–6725. National Acad Sciences

Binzer A, Guill C, Brose U, Rall BC (2012) The dynamics of food chains under climate change and nutrient enrichment. Philos Trans R Soc B Biol Sci 367(1605):2935–2944. The Royal Society

Brander KM (2007) Global fish production and climate change. Proc Natl Acad Sci 104(50): 19709–19714. National Acad Sciences

Bryant D, Burke L, McManus J, Spalding M (1998) Reefs at risk: a map-based indicator of threats to the world's coral reefs. WRI/ICLARM/WCMC/UNEP, Washington, DC

Chassot E, Bonhommeau S, Dulvy NK, Mélin F, Watson R, Gascuel D, Le Pape O (2010) Global marine primary production constrains fisheries catches. Ecol Lett 13(4):495–505. Wiley Online Library

Daufresne M, Lengfellner K, Sommer U (2009) Global warming benefits the small in aquatic ecosystems. Proc Natl Acad Sci 106(31):12788–12793. National Acad Sciences

Daw T, Adger WN, Brown K, Badjeck M-C (2009) Climate change and capture fisheries: potential impacts, adaptation and mitigation

Dey S, Srivastava PK, Maji S, Das MK, Mukhopadhyaya MK, Saha PK (2007) Impact of climate change on the breeding of Indian major carps in West Bengal. J Inland Fish Soc India 39(1): 26–34

Harvell CD, Kim K, Burkholder JM, Colwell RR, Epstein PR, Grimes DJ, Hofmann EE, Lipp EK, Osterhaus A, Overstreet RM (1999) Emerging marine diseases–climate links and anthropogenic factors. Science 285(5433):1505–1510. American Association for the Advancement of Science

Hobday AJ, Pecl GT (2014) Identification of global marine hotspots: sentinels for change and vanguards for adaptation action. Rev Fish Biol Fish 24:415–425

Huang M, Ding L, Wang J, Ding C, Tao J (2021) The impacts of climate change on fish growth: a summary of conducted studies and current knowledge. Ecol Indic 121:106976. Elsevier

IPCC Core Writing Team (2007) Climate change 2007: synthesis report. IPCC Geneva, Switzerland

Kelleher K, Willmann R, Arnason R (2009) The sunken billions: the economic justification for fisheries reform. The World Bank

McGinnity P, Jennings E, DeEyto E, Allott N, Samuelsson P, Rogan G, Whelan K, Cross T (2009) Impact of naturally spawning captive-bred Atlantic salmon on wild populations: depressed recruitment and increased risk of climate-mediated extinction. Proc R Soc B Biol Sci 276(1673):3601–3610. The Royal Society

Menon AGK (1954) Fish geography of the Himalayas. National Institute of sciences of India

Mohanty B, Mohanty S, Sahoo J, Sharma A (2010) Climate change: impacts on fisheries and aquaculture. Clim Change Var 119:978–953. ISBN

Mumby PJ, Harborne AR (2010) Marine reserves enhance the recovery of corals on Caribbean reefs. PLoS One 5(1):e8657. Public Library of Science San Francisco

Nicholls RJ et al (2007) Coastal systems and low-lying areas

Orr JC, Fabry VJ, Aumont O, Bopp L, Doney SC, Feely RA, Gnanadesikan A, Gruber N, Ishida A, Joos F (2005) Anthropogenic Ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437(7059):681–686. Nature Publishing Group

Pecl GT et al (2014) Rapid assessment of fisheries species sensitivity to climate change. Clim Chang 127:505–520

Prowse TD, Furgal C, Wrona FJ, Reist JD (2009) Implications of climate change for northern Canada: freshwater, marine, and terrestrial ecosystems. Ambio 38(2):282–289. JSTOR

Rosenzweig ML (1971) Paradox of enrichment: destabilization of exploitation ecosystems in ecological time. Science 171(3969):385–387. American Association for the Advancement of Science

Sarmiento JL, Slater R, Barber R, Bopp L, Doney SC, Hirst AC, Kleypas J, Matear R, Mikolajewicz U, Monfray P (2004) Response of ocean ecosystems to climate warming. Glob Biogeochem Cycles 18(3). Wiley Online Library

Shao K-T (2009) Marine biodiversity and fishery sustainability. Asia Pac J Clin Nutr 18(4): 527–531

Vass KK, Das MK, Srivastava PK, Dey S (2009) Assessing the impact of climate change on inland fisheries in River Ganga and its plains in India. Aquat Ecosyst Health Manag 12(2):138–151. Michigan State University Press

Verma AK (2016) Biodiversity: its different levels and values. Int J Environ Sci 7(2):143–145

Verma AK (2017) Environmental ethics: need to rethink. Int. J Environ Sci 8(1):7–9

Verma AK (2019) Sustainable development and environmental ethics. Int J Environ Sci 10(1):1–5

Walther G-R, Roques A, Hulme PE, Sykes MT, Pyšek P, Kühn I, Zobel M, Bacher S, Botta-Dukat Z, Bugmann H (2009) Alien species in a warmer world: risks and opportunities. Trends Ecol Evol 24(12):686–693. Elsevier

Climate Change and Coral Reef Ecosystem: Impacts and Management Strategies

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Abstract

Coral reefs are one of the most diversified ecosystems globally, providing food and shelter to a wide variety of organisms. It serves as a mutual relationship for various marine fauna. It also offers multiple ecological services and goods and is an integral part of income generation through tourism and recreational activities. Despite their significant value, coral reefs are cladding substantial challenges from the global climate change phenomenon led by various anthropogenic activities. Global warming is a subset of the broader phrase climate change. It specifies the observed rise in the average air temperature near the earth's surface and seas due to the rapid increase in greenhouse gases caused by numerous anthropogenic activities. Coral bleaching, destruction in the reef structure, ocean acidification, increased coral diseases, etc., are various consequences faced by the coral reefs due to climate change. Overall, climate change can drastically alter the ecosystem's biodiversity spectrum, function, and

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productivity. Cooperative solid action is required to lessen the climate change effects on the global scale and its repercussion on corals.

Keywords

Anthropogenic activity · Carbon sequestration · Climate change · Coral bleaching · Polyps · Coral disease

1 Introduction

Worldwide coral reefs are one of the multifarious biologically diverse ecosystems. The animals primarily responsible for producing reefs are the coral polyps which can take numerous shapes such as vast reef-building colonies, exquisite flowing fans, and sometimes tiny, solitary organisms. They are unique ecosystems because of their biological (coral) and ecological (reef) constituents. Including deep-sea corals, >6000 species of corals had been identified globally, many of which inhabit warm, superficial, tropical seas and others in the cold, gloomy depths of the ocean floor (NOAA 2019). They provide ecosystem services such as food provision, livelihood possibilities, carbon sequestration, and storm protection to tropical and subtropical regions, small-island developing states, and indigenous peoples (Eddy et al. 2021). But over the last two decades, stakeholders have been increasingly concerned about anthropogenic-induced climate change and global warming. In ongoing studies into the effects of climate change, it has become abundantly evident that coral reefs are one of the most vulnerable ecosystems to this phenomenon. Apart from climate change, they are also affected by pollution, overfishing, and habitat destruction. The combined effect of these factors on coral reefs' global capacity to offer ecosystem services is uncertain. The well-being and sustainable coastal development of human settlements that rely on coral reef ecosystem services are challenged by the expected ongoing degradation of coral reefs and accompanying loss of biodiversity and fisheries catch (Eddy et al. 2021). Climate change puts the world's coral reefs as well as the ocean ecosystems and human economies they sustain in jeopardy. In the tropics, where water temperatures are on average warmer and warming oceans are pushing corals to their limits, the situation is much more difficult (Bourzac 2020).

A region's climate represents average weather over a longer length of time. In contrast, climate change is a statistically significant shift in either the mean state of the climate or its statistical features that last for decades or more (Ninawe et al. 2018). Besides being a major worldwide environmental issue, it is also a significant source of concern for emerging countries such as India. Because it has developed as a new pressing problem that has a complex impact on resources, resource users, and the environment, it has been dubbed the most pressing environmental issue of the twenty-first century, and it has sparked a lot of discussion and debate. It is expected to have negative, irreversible consequences for the planet and the ecosystem as a whole. Although it is difficult to link specific weather events to climate change, rising global temperatures are expected to result in broader effects such as glacial retreat, Arctic shrinkage, and global sea-level rise. Several aquatic species, including plants, fish, corals, and animals, have died in large numbers due to climate change.

Global warming is a subset of the broader phrase “Climate Change,” and it refers to the recent increase in the average temperature of the air at the earth’s surface and the seas. It is the artificial rise in the earth’s temperature and the temperature of the atmosphere layers closest to the planet due to an intensive increase in certain gases such as greenhouse gases that occur as a result of various anthropogenic activities. In 2017, human-caused warming had already surpassed 1 °C beyond pre-industrial levels. Warming reached 0.87 °C (±0.12 °C) in the decade 2006–2015, compared to pre-industrial times (1850–1901), owing primarily to human activities increasing the volume of greenhouse gases in the atmosphere. The global temperature is rising at a rate of 0.2 °C (±0.1 °C) per decade. If the current rate of warming continues, the world will hit 1.5 °C of human-caused global warming around 2040 (IPCC 2019).

2 Coral Reefs and Global Climate Change

Global climate change excitingly affects coral reef ecosystems in the following ways:

Coral reefs are one of the first instances of how rapid anthropogenic climate change could negatively influence biological systems. A novel phenomenon known as mass coral bleaching first appeared in the scientific literature in the early 1980s. Due to a rise in the surrounding temperature, the warming of the water layer takes place. As corals are extremely sensitive to temperature changes, the warming causes significant thermal stress to the coral reef ecosystems leading to a phenomenon called coral bleaching. Increased water temperatures due to global warming can cause mass coral bleaching. When the heat tolerance of corals and their photosynthetic symbionts (zooxanthellae) is surpassed, coral bleaching occurs. Corals will eject the algae (zooxanthellae) that live in their tissues if the water is too warm, causing the coral to turn entirely white or bleached. Almost 30 years ago, the first report of mass coral bleaching was reported, but recently, most coral reefs have experienced it regularly. Measurements of sea surface temperature (SST) from remote observations have also helped confirm the underlying cause of coral bleaching and predict future changes to coral reefs due to the rapid warming of tropical and subtropical oceans. Satellite observations have confirmed that if sea temperature rises by 1 °C above the long-term summer maximum temperatures in a given region, mass bleaching is quite likely (Strong et al. 1996; Toscano et al. 2000). The amount of time a coral reef zone is exposed to a particular anomaly has been factored into these calculations. Corals can recover after brief bleaching episodes, but as the duration and severity of the stress increase, so does coral mortality. As sea temperatures rise, coral bleaching events and consequent reef death are predicted to become more common (TCRA 2005).

No doubt that global warming is a significant threat to coral reef ecosystems, but various authors have proposed that ocean acidification caused by increasing concentration of atmospheric CO_2 posed a severe additional threat (Kleypas et al. 1999a, 1999b). The phrase "ocean acidification" was coined to describe this phenomenon, and it is now widely recognized as a severe hazard to marine calcifiers, including coral reefs (Caldeira and Wickett 2003). The primary effect of climate change faced by the ocean is ocean acidification. Ocean acidification occurs due to increased concentration of carbon dioxide (CO_2) which will reduce the pH of the ocean water. The reduction of ocean pH acidifies the coral reefs by decreasing the somatic growth of coral reefs and structural integrity. It occurs due to increased carbon dioxide flow into ocean waters as a result of rising atmospheric CO_2 concentrations. Carbon dioxide combines with water molecules in the ocean to form carbonic acid. After that, carbonic acid dissociates, releasing a proton, which combines with carbonate ions to form bicarbonate ions. Carbonate ion concentrations are frequently expressed in aragonite, the most common crystal form of calcium carbonate crystals deposited by reef-building corals and other marine calcifiers. If the atmospheric carbon dioxide levels were doubled, their ability to create calcium carbonate skeletons would be considerably reduced (by up to 40%), as reported by Kleypas et al. (1999b).

Another impact of climate change is the rising sea levels of the oceanic environment. When heated by elevated temperature, the water tends to expand, i.e., oceans take up more space. Additionally, the melting of ice glaciers and ice caps increases the flow of additional water into the sea, causing the sea levels to rise. Due to this, the sedimentation loads increase in the ocean, affecting the coral reefs in various ways. When silt and other contaminants enter the water, they suffocate coral reefs by speeding the growth of harmful algae and lowering water quality. Pollution can also render corals more susceptible to infectious diseases, stifle coral growth and reproduction, and alter the reef's food web. Also, due to rising sea levels, the coral will be deeper and receive less sunlight, causing it to grow slower. The coalescence effect of deeper reefs and slower growth will cause problems for coastal areas because corals will be less able to protect the shore as effectively, and wave energy may increase strength (TCRA 2005). Smaller reefs will also produce less reef sediment, which builds and supports less biodiversity and life. The frequency, intensity, and impacts of numerous types of extreme weather events are expected to increase due to climate change. Rising sea levels, for example, exacerbate the effects of coastal storms, and warming can put more strain on water supplies during droughts. Extreme weather events will cause stronger and more frequent cyclonic storms that will affect the coral reefs by changing or destroying the reef structure. As storms and cyclones become more frequent and intense, coral mortality is predicted to rise. Due to climate change phenomena, various cyclonic storms and tsunamis frequently occur along the Indian coast. A tsunami can affect coral reefs in multiple ways. The tsunami's impact on coral reefs in the Indian Ocean in 2004 varied dramatically on scales ranging from intra-reef to international. Tsunamis have altered the geomorphology of the reefs along the coast. The expansion of coral reefs may not keep up with these catastrophic events.

Climate change also changes the precipitation patterns due to different cyclonic storms occurring unevenly during the year, causing uneven and extended rainfall.

This extended rainfall pattern increases the freshwater runoff, increased sediment, and land-based pollutants. This will cause murky water conditions, which will restrict the light penetration and slower growth rates of coral reefs. This will also cause tweaked water currents, altering the association and temperature pattern. Due to this, starvation of the reefs and associated fauna will occur due to a lack of food supply and restricted larval dispersal. Climate change events will increase coral mortality and put coral reefs at grave risk, particularly those already under stress. These climatic changes could be a well-known provocation for reefs already under stress from poor water quality, destructive fishing, and tourism.

A variety of other critical characteristics for near-shore tropical ecosystems are predicted to change as greenhouse gas concentrations rise. Suppose the current moderate pace of change continues, and organisms such as reef-building corals stay healthy enough to keep up with the changes in water depth. In that case, changing sea levels are unlikely to constitute a significant hazard. While there is a lot of disagreement in the projections for sea-level rise, several top research groups predict that by 2100, the average sea level will have risen by 1.4 m or more (Rahmstorf 2007). These projections may be conservative, giving indications of the accelerated disintegration of the terrestrial ice sheets in Greenland (Witze 2008) and Western Antarctica (Steig et al. 2009), which suggest that current IPCC forecasts of 30–50 cm by 2100 (IPCC 2007) greatly underestimate the potential for a sea-level rise if water and ice input from these sources rises. Changing weather patterns along coral reef-fringed beaches are also anticipated to impact coral reef health in the future. The flow of nutrients and sediments from coastal areas has a significant impact on whether coral reefs thrive or not. Warmer oceans are likely to produce more severe storms (IPCC 2007), raising the possibility that some coral reefs could suffer increased damage from more frequent destructive storms. Changing rainfall patterns and storm severity may contribute to the destabilization and erosion of river catchments, which eventually discharge into waters that plunge coastal ecosystems like coral reefs. These climatic changes could become the axiomatic hay that degrades the aesthetic integrity of coral reefs with increased stressors such as dreadful physico-chemical water quality, unsustainable fishing practices, and tourism and sports activities.

3 Effect of Climate Change on Coral Diseases

Over the past three decades, the health of the world's coral reefs has gradually declined. The essential driver of this decline is increased shallow ocean temperatures, which stress the normal metabolism of corals and change the normal microbiota associated with healthy colonies. Diseases in corals have been observed upon exposure to increased seawater temperatures and reported for both gorgonian (Harvell et al. 2001) and scleractinian (Rosenberg and Ben-Haim 2002; Jones et al. 2004) corals. Several bacterial, fungal, and protozoan diseases of corals are coupled to increased ocean temperatures, including black band disease (Muller and van Woesik 2014) caused by bacteria *Phormidium corallyticum*, yellow band disease

(Cervino et al. 2008; Harvell et al. 2009) caused by *Vibrio charchariae*, and white syndromes (Bruno et al. 2007; Greene et al. 2020). The bacterial genera Vibrio causes coral bleaching, and the adhesion of the bacterium to the coral surface is temperature-dependent (Toren et al. 1998). *Vibrio charchariae* was identified as the etiology of the white-band disease (Gil-Agudelo et al. 2006), also associated with increased temperatures. Cervino et al. (2008) isolated a consortium of four Vibrio species as etiological agents—*Vibrio rotiferianus*, *Vibrio harveyi*, *Vibrio alginolyticus*, and *Vibrio proteolyticus* from corals with the yellow-band disease. This highly infectious disease affects both Caribbean and Indo-Pacific reef-building coral species. Further, a clear link has been established between the increased rate of spread of yellow-band disease and high sea surface temperatures (Cervino et al. 2005).

4 Effects of Climate Change on Coral Reef Fishes

Climate change poses a serious threat to coral reef ecosystems and will have various consequences for coral reef fish. Climate change primarily contributes to the widespread degradation of coral reef environments, resulting in decreases in the abundance and variety of reef-associated fishes. Furthermore, rising temperatures will directly impact the individual health and fitness of some coral reef fishes. Unless these species can adjust to shifting temperature regimes, they are likely to persist in only a tiny fraction of their current geographic range or migrate poleward, invading new habitats and displacing other fish species. Finally, rising CO_2 levels and ocean acidification may have substantial physiological and behavioral consequences for fish in the latter half of this century (Pratchett et al. 2015). Global climate change can drastically alter ecosystem biodiversity, function, and productivity. So far global climate change has manifested itself primarily as an increase in the incidence of mass bleaching and disease among scleractinian corals and other zooxanthellate organisms, which is directly contributing to the widespread degradation of coral reef habitats and will be exacerbated by the effects of ocean acidification (Pratchett et al. 2015). Studies on the impact of climate change on the behavior and assemblages of some coral reef fishes are given in Table 1.

5 Measures to Protect Coral Reefs from Climatic Impacts

To preserve coral reefs safe and healthy, there are a variety of activities that may be done. While several dangers to coral reefs occur immediately on the sea, some terrestrial activities distant from the shore can also impact coral reefs. Pollution, material deterioration, harmful fishing operations, alluviation, and excessive utilization can directly impact the health of coral reefs and other productive shallow-water ecosystems and can thus be managed directly. Below are the several measures to be taken to reduce the climatic changes and impacts on coral reefs:

Table 1 Impacts of global climate change on coral reef fishes

Species	Location	Impact	Reference
Lutjanus ehrenbergii, *Pomacanthus maculosus*	Arabian Gulf	Reduced growth	D'Agostino et al. (2021)
Abudefduf vaigiensis	Southeast Australia	Reduced foraging performance	Coni et al. (2021)
Acanthochromis polyacanthus	Palm Islands regions of Central Great Barrier Reef	Reproductive output and offspring quality	Spinks et al. (2021)
Pomacentrus trichrourus	Arabian/Persian Gulf waters	Change in feeding dynamics and reduced distance from refugia	D'Agostino et al. (2020)
Reef fishes	Kiritimati (Republic of Kiribati; Central equatorial Pacific)	The decline in reef fish biomass	Magel et al. (2020)
Reef fishes	Worldwide	Changes in reef fish assemblages	Pratchett et al. (2018)
Reef fishes	Lizard Island, Northern Great Barrier Reef	Biotic homogenization of reef fish assemblages	Richardson et al. (2018)
Reef fishes	Apo Island, Philippines	The decline in species richness and abundance	Abesamis et al. (2018)
Dischistodus perspicillatus, *Dascyllus aruanus*, *A. polyacanthus*	Lizard Island, Northern Great Barrier Reef	Reduce maximum thermal limits of fish	Clark et al. (2017)
Pomacentrus wardi and *Pseudochromis fuscus*	Lizard Island, Northern Great Barrier Reef	Increase in predation (prey-predator relationship)	Allan et al. (2015)
Amphiprion melanopus	Palm Islands regions of Central Great Barrier Reef	Increase in metabolic rate and decreases in length, weight, condition, and survival of juvenile fish	Miller et al. (2012)
Neopomacentrus azysron	Lizard Island, Northern Great Barrier Reef	Behavioral lateralization	Domenici et al. (2012)
Amphiprion melanopus	Orpheus Island of Central Great Barrier Reef	Decreases foraging and feeding activities of fish	Nowicki et al. (2012)
Acanthochromis polyacanthus	Orpheus Island of Central Great Barrier Reef	Reduced capacity for growth	Munday et al. (2008)

Lessen the Carbon Footmark to Reduce GHGs Since the mid-twentieth century, GHGs from anthropogenic activities have been the major contributor to climate change. Thus, reducing the emission of carbon dioxide is crucial to protect the environment and coral reefs from the harmful effects of climate change. To achieve this, individual efforts are necessary. Purchase energy-efficient light bulbs and other electrical appliances. Print the documents if it is essential and download more. Always use less water and conserve water to save the environment and coral reefs from the climatic impacts. Reduce subsidies on fossil fuels to further reduce the emission of harmful gases in the environment and protect the coral reef ecosystem.

Use the Environment-Friendly Mode of Transportation Always use public transport (or walk) and drive less so that there will be less emission of CO_2 in the environment. Buy a fuel-efficient vehicle such as electric and gas-operated vehicles to reduce harmful gases in the atmosphere.

Implement Safe and Responsible Diving and Parasailing Shun touching and extracting reefs because contact with these delicate coral reefs will harm the animals. Avoid anchoring the fishing crafts near the reef areas. Always take a reef-friendly approach while scuba diving or parasailing.

Apply 3 R's Strategy (Reduce, Reuse, and Recycle) Minimize (or stop) the use of single-use plastics in daily life and properly dispose of the plastic wastes into the bins so that they will not be carried to oceans. Recycle trash at home so that best can be manufactured from waste.

Minimize Application of Fertilizers The overuse of fertilizer can deteriorate water quality by overwhelming nutrients or by harmful heavy metals in the water, affecting the coral reefs and their ecosystem.

Save Energy Turn off lights, and other electrical devices unnecessarily kept on. Invest in energy-efficient appliances, such as those that have received the Energy Star certification; when you leave work, attempt to turn off the lights and your computer.

Awareness Program Explore more about the importance of coral reefs and educate the local community. Different awareness programs are required to share the importance of coral reefs and their associated flora and fauna with the local peoples, stakeholders, school children, and everyone in society. Contact the local authority to know about the measures taken by the district-level, state-level, and country-level representatives to protect the coral reefs and the water quality of the oceanic environment.

Acquire Policies and Treaties to Minimize GHGs Emissions and Climate Change Various policies and regulations are required for proper carbon sequestration and restrictions on releasing harmful GHGs from the industries. The severity of global climate change will be lessened when greenhouse gas emissions are reduced. All countries have persuaded the Kyoto Climate Change Convention to support, adopt, and implement it. They are also urged to participate in the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC) programs.

Protect and Enhance Ecosystems Natural carbon sequestration is a tactic that governments can use to reduce the severity of climate change by maintaining and developing forests and wetlands. The act of absorbing carbon dioxide from the atmosphere by increasing ecosystems that absorb greenhouse gases, such as forests, is known as natural carbon sequestration. Carbon sequestration should be considered the primary management strategy (TCRA 2005).

Research and Monitoring Continue to strengthen environmental monitoring programs to make management decisions based on the most up-to-date information, and management methods may be adjusted to cope with changing circumstances. Continue to build research capacity in the specific region dealing with management concerns.

Building a Solid Foundation Different foundations need to be set up to strengthen the coral reef monitoring programs by purveying financial support and training. It will help establish and conduct the socio-economic surveillance of the coral reef-dependent fishing and tourism sectors and tribal level monitoring within the coastal communities.

Apart from the above mentioned strategies coral reefs can be protected from the climatic impacts in the following ways (Arenschield 2020):

Restriction on the use of chemicals that destroy coral reefs, including reef-friendly sunscreens and apparel with a UV protection factor.
Consuming food that is produced sustainably and supplied locally.
Voting for policies that promote environmental protection and help to minimize greenhouse gas emissions.
Promoting science-based decision-making and reef preservation.
Getting the word out to policymakers that coral reef protection is a top priority.
Single-use plastics are being avoided.
Reducing energy consumption.
Participating in local efforts that support coral reefs, such as coastal cleanups and philanthropy.
Educating yourself and others about the coral reefs threats and the best strategies to protect them.
Getting others to sign the pledge.
To maintain coral reefs and mitigate the effects of climate change on the ecosystem, local, national, and international collaboration is essential.

6 Pyramid of Conservation

A pyramid of conservation action is required to reduce and minimize the impacts of climate change on the coral reefs and ecosystems as a whole. At the base of the pyramid conservation action, local community action is required to reduce and manage provincial threats. After that determination of the conservation, a strategy is needed to recognize principal threats and their solutions. Finally, prioritized investments are crucial to investing in big long-term planning projects to solve the problem or minimize the impacts of climate change (Hoegh-Guldberg et al. 2018).

7 Conclusion

Coral reef ecosystems are at confederation of two significant communal courses, one serving a vast resource to the growing human population and another being ontologically threatened by increased climate change phenomenon caused by the various anthropogenic pressures. Due to global warming and the general rise in the surrounding temperature, the extensive coral mortality from severe bleaching events has been causing devastating effects on the coral reef communities. Continuing disease threats and concerns about increasingly acidifying waters intensify the risk posed to coral reefs. Different cooperative strategies especially shrinking the carbon footprint will mitigate the intensified impact on the highly diverse ecosystems. Further, essential interventions are required to explore that enhance the endurance and adaptability of coral reefs to the on-going deleterious environmental conditions.

References

Abesamis RA, Langlois T, Birt M, Thillainath E, Bucol AA, Arceo HO, Russ GR (2018) Benthic habitat and fish assemblage structure from shallow to mesophotic depths in a storm-impacted marine protected area. Coral Reefs 37(1):81–97

Allan BJ, Domenici P, Munday PL, McCormick MI (2015) Feeling the heat: the effect of acute temperature changes on predator–prey interactions in coral reef fish. Conserv Physiol 3(1):1–8

Arenschield A (2020) 12 things you can do to help save coral reefs. Ohio State News. https://news.osu.edu/12-things-you-can-do-to-help-save-coral-reefs

Bourzac K (2020) Climate change is destroying our coral reefs. Here's how scientists plan to save them. Chem Eng News 98(6)

Bruno JF, Selig ER, Casey KS, Page CA, Willis BL, Harvell CD, Sweatman H, Melendy AM (2007) Thermal stress and coral cover as drivers of coral disease outbreaks. PLoS Biol 5(6):e124

Caldeira K, Wickett ME (2003) Anthropogenic carbon and ocean pH. Nature 425:365

Cervino JM, Littler MM, Littler DS, Polson S, Goreau TF, Brooks BL, Smith GW (2005) Identification of microbes associated with coralline lethal algal disease and its relationship to glacial ice melt (global warming). Phytopathology 95:6

Cervino JM, Thompson FL, Gomez-Gil B, Lorence EA, Goreau TJ, Hayes RL, Winiarski-Cervino KB, Smith GW, Hughen K, Bartels E (2008) The Vibrio core group induces yellow band disease in Caribbean and Indo-Pacific reef-building corals. J Appl Microbiol 105(5):1658–1671

Clark TD, Roche DG, Binning SA, Speers-Roesch B, Sundin J (2017) Maximum thermal limits of coral reef damselfishes are size dependent and resilient to near-future ocean acidification. J Exp Biol 220(19):3519–3526

Coni EO, Booth DJ, Nagelkerken I (2021) Novel species interactions and environmental conditions reduce foraging competency at the temperate range edge of a range-extending coral reef fish. Coral Reefs 40(5):1525–1536

D'Agostino D, Burt JA, Reader T, Vaughan GO, Chapman BB, Santinelli V, Cavalcante GH, Feary DA (2020) The influence of thermal extremes on coral reef fish behaviour in the Arabian/Persian Gulf. Coral Reefs 39(3):733–744

D'Agostino D, Burt JA, Santinelli V, Vaughan GO, Fowler AM, Reader T, Taylor BM, Hoey AS, Cavalcante GH, Bauman AG, Feary DA (2021) Growth impacts in a changing ocean: insights from two coral reef fishes in an extreme environment. Coral Reefs 40(2):433–446

Domenici P, Allan B, McCormick MI, Munday PL (2012) Elevated carbon dioxide affects behavioural lateralization in a coral reef fish. Biol Lett 8(1):78–81

Eddy TD, Lam VW, Reygondeau G, Cisneros-Montemayor AM, Greer K, Palomares MLD, Bruno JF, Ota Y, Cheung WWL (2021) Global decline in capacity of coral reefs to provide ecosystem services. One Earth 4(9):1278–1285

Gil-Agudelo DL, Myers C, Smith GW, Kim K (2006) Changes in the microbial communities associated with *Gorgonia ventalina* during aspergillosis infection. Dis Aquat Org 69(1):89–94

Greene A, Donahue MJ, Caldwell JM, Heron SF, Geiger E, Raymundo LJ (2020) Coral disease time series highlight size-dependent risk and other drivers of white syndrome in a multi-species model. Front Mar Sci 7:601469

Harvell D, Kim K, Quirolo C, Weir J, Smith G (2001) Coral bleaching and disease: contributors to 1998 mass mortality in *Briareum asbestinum* (Octocorallia, Gorgonacea). Hydrobiologia 460(1):97–104

Harvell D, Altizer S, Cattadori IM, Harrington L, Weil E (2009) Climate change and wildlife diseases: when does the host matter the most? Ecology 90(4):912–920

Hoegh-Guldberg O, Kennedy EV, Beyer HL, McClennen C, Possingham HP (2018) Securing a long-term future for coral reefs. Trends Ecol Evol 33(12):936–944

IPCC (2007) Synthesis report. In: Core Writing Team, Pachauri RK, Reisinger A (eds) Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change. Intergovernmental Panel on Climate Change, Geneva, p 104

IPCC (2019) An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In: Global warming of 1.5°C, pp 80–81

Jones RJ, Bowyer J, Hoegh-Guldberg O, Blackall LL (2004) Dynamics of a temperature-related coral disease outbreak. Mar Ecol Prog Ser 281:63–77

Kleypas JA, McManus JW, Menez LAB (1999a) Environmental limits to coral reef development: where do we draw the line? Am Zool 39:146–159

Kleypas JA, Buddemeier RW, Archer D, Gattuso JP, Langdon C, Opdyke BN (1999b) Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. Science 284:118–120

Magel JM, Dimoff SA, Baum JK (2020) Direct and indirect effects of climate change amplified pulse heat stress events on coral reef fish communities. Ecol Appl 30(6):e02124

Miller GM, Watson SA, Donelson JM, McCormick MI, Munday PL (2012) Parental environment mediates impacts of increased carbon dioxide on a coral reef fish. Nat Clim Chang 2(12): 858–861

Muller EM, van Woesik R (2014) Genetic susceptibility, colony size, and water temperature drive white-pox disease on the coral *Acropora palmata*. PLoS One 9(11):e110759

Munday PL, Kingsford MJ, O'Callaghan M, Donelson JM (2008) Elevated temperature restricts growth potential of the coral reef fish *Acanthochromis polyacanthus*. Coral Reefs 27(4): 927–931

Ninawe AS, Indulkar ST, Amin A (2018) Impact of climate change on fisheries. In: Biotechnology for sustainable agriculture. Woodhead Publishing, pp 257–280

NOAA (2019) Coral reef ecosystems. National Oceanic and Atmospheric Administration US Department of Commerce. https://www.noaa.gov/education/resource-collections/marine-life/coral-reef-ecosystems

Nowicki JP, Miller GM, Munday PL (2012) Interactive effects of elevated temperature and CO2 on foraging behavior of juvenile coral reef fish. J Exp Mar Biol Ecol 412:46–51

Pratchett MS, Wilson SK, Munday PL (2015) 13 Effects of climate change on coral reef fishes. In: Mora C (ed) Ecology of fishes on coral reefs, vol 127. Cambridge University Press

Pratchett MS, Thompson CA, Hoey AS, Cowman PF, Wilson SK (2018) Effects of coral bleaching and coral loss on the structure and function of reef fish assemblages. In: Coral bleaching. Springer, Cham, pp 265–293

Rahmstorf S (2007) A semi-empirical approach to projecting future sea-level rise. Science 315: 368–370

Richardson LE, Graham NAJ, Pratchett MS, Eurich JG, Hoey AS (2018) Mass coral bleaching causes biotic homogenization of reef fish assemblages. Glob Chang Biol 24(7):3117–3129

Rosenberg E, Ben-Haim Y (2002) Microbial diseases of corals and global warming. Environ Microbiol 4(6):318–326

Spinks RK, Bonzi LC, Ravasi T, Munday PL, Donelson JM (2021) Sex-and time-specific parental effects of warming on reproduction and offspring quality in a coral reef fish. Evol Appl 14(4): 1145–1158

Steig EJ, Schneider DP, Rutherford SD, Mann ME, Comiso JC, Shindell DT (2009) Warming of the Antarctic ice-sheet surface since the 1957 international geophysical year. Nature 457:459–462

Strong AE, Barrientos CS, Duda C, Sapper J (1996) Improved satellite technique for monitoring coral reef bleaching. In: Proceedings of the eighth international coral reef symposium, Panama, June 1996, pp 1495–1497

TCRA (2005) Coral reefs and global climate change. The Coral Reef Alliance (CORAL), San Francisco, CA

Toren A, Landau L, Kushmaro A, Loya Y, Rosenberg E (1998) Effect of temperature on adhesion of *Vibrio* strain AK-1 to *Oculina patagonica* and on coral bleaching. Appl Environ Microbiol 64 (4):1379–1384

Toscano MA, Liu G, Guch IC, Casey KS, Strong AE, Meyer JE (2000) Improved prediction of coral bleaching using high-resolution hotspot anomaly mapping. In: Proceedings of the ninth international coral reef symposium, Bali, vol 2, pp 1143–1147

Witze A (2008) Losing Greenland. Nature 452:798–802

Implications of Climate Change on Fisheries and Food Security

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and Suchismita Jana

Abstract

Climate change is a burning issue in recent times which induces natural calamities like drought, flood, etc., and also reduces the freshwater resources, resulting in a reduction in food production. Insufficient food availability leads to labor migration and food insecurity, and loss of livelihood and purchasing power of rural poor people. Not only agricultural production, but climate change affects fisheries production also. As Asia is having the highest population, food demand is also high and in consequence, an increasing number of people are suffering from adverse effects of climate change. To mitigate food insecurity, National Food Security Act needs to be followed which has aim to improve household food security.

Keywords

Climate change · Fisheries · Food security · Livelihood · Sustainability

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1 Introduction

The world population is likely be to be expected about 9.8 billion by 2050 (United Nations 2017) and there is a necessity for about a 50% increase in food production globally by 2050 (FAO 2017) to overcome the problems of hunger and malnutrition worldwide. Protein is a vital component of our diet for healthy living. Fisheries make a major contribution of animal protein to the human food supply and security. Food security is defined as "secure access to enough food at all times" (Kent 1997). As fish is very nutritious, so adding even a small quantity can make a big change in people's diet and health. Fish contains some vital nutrients which are not present in typical starchy staple foods (FAO 2005). Thorpe et al. (2006) reported that about 20 percent of global animal protein intake is contributed by fish and provides food security by creating revenue for food-deficient countries to purchase food. A huge number of people are directly involved in fisheries and aquaculture which is conservatively estimated at 43.5 million. About 90 percent of employment in fisheries is from small-scale fishers. In addition to those, there are "forward linkages" and "backward linkages" (Figs. 1, 2, and 3) where people are indirectly involved in various

Fig. 1 Linkage in fisheries sector

Fig. 2 Backward linkages

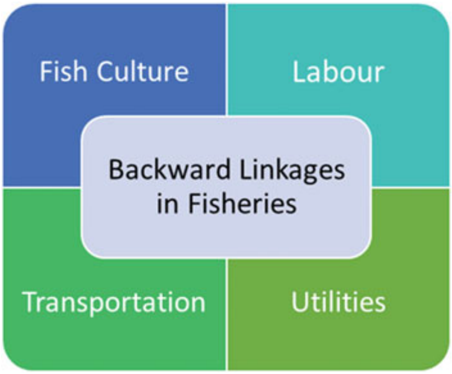
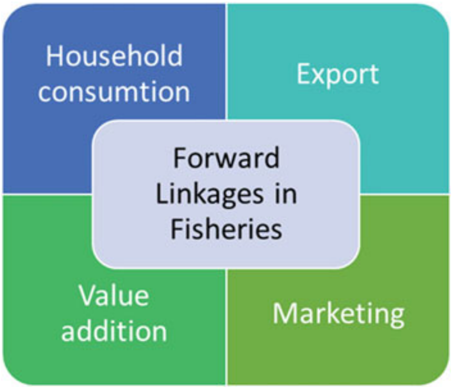


Fig. 3 Forward linkages



activities. These activities also help in income generation through post-harvest activities, especially processing and marketing. Supporting activities in fisheries like fishing craft and gear making, and engineering aspects of fishing are also a part of national income generation.

A fishery may serve as a “safety net” for landless poor in that remote area where another economic source is limited (FAO 2005). In recent years, fish production is declining in the capture sector due to overfishing, capturing of endangered species, pollution, and other environmental stresses, most importantly because of climate change. Global bio-physiological, social, and economic environments are under threat as the climate is changing continually (Tiyo et al. 2015). Changes in temperature, as well as rainfall, are directly affecting the crop production system including fisheries (Rice and Garcia 2011).

The impacts of climate change on the ocean are as follows:

1. Increase in sea level (average 3 mm per year).
2. Degradation of the ocean ecosystem.
3. The salinity of coastal areas in both surface and groundwater is changing.
4. Increased temperature, changing ocean chemistry, acidification of the ocean, and frequent storm hampering the marine ecosystem.
5. The ocean warms affecting the marine stock and reducing average catches.
6. Threat to humans dependent on ocean resources for their livelihood and nutrition.

2 Effect of Climate Change on Fisheries

Climate change has a direct impact on existing drivers, trends, and the status of fisheries. There was a report by the Food and Agriculture Organization of the United Nations (FAO) that marine fisheries production peaked in the 1980s among which approximately half of the fisheries have been exploited in recent years to their maximum capacity, one quarter overexploited, and the last quarter has the potential to increase production (FAO 2007). It has been identified that developing countries

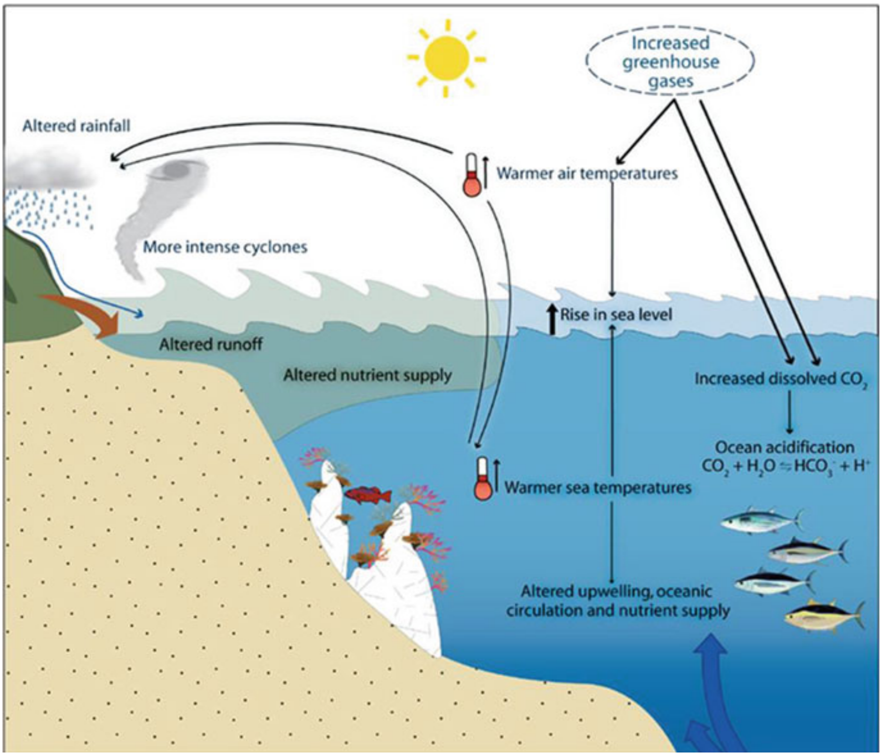


Fig. 4 Effect of climate change on oceanic and coastal ecosystem. (Source: accessed from http://www.franciscoblaha.info/blog/2015/11/23/climate-change-and-fisheries)

in tropical regions are vulnerable to climate change as they are economically and nutritionally dependent on fisheries (Barange et al. 2018). The fisheries sector is affected by climate change in different ways which are depicted below (Fig. 4) according to Francisco Blaha (2015) who described the effect of increased greenhouse gases on the oceanic ecosystem.

2.1 Physical and Biogeochemical Changes

The physical and chemical properties of the ocean are getting altered due to climate change. These changes include warming, rising sea level, decreasing oxygen level, CO_2 emission, acidification (reduction of soil and/or water pH), and nutrient concentrations reduction (Barange et al. 2018; Pörtner et al. 2019; Bindoff et al. 2013). The ocean absorbs and accumulates more the 90% of energy and gets warmed due to rising anthropogenic greenhouse gas concentrations (Abram et al. 2019; Cheng et al. 2020) which have devastating impacts on marine ecosystems (Frölicher and Laufkötter 2018; Smale et al. 2019).

2.2 Changes in Productivity of Fish Stocks

Optimum environmental condition is desirable for the proper growth of fishes. Global climate change and ocean environment (temperature, ocean chemistry) change causing stress to fishes due to which growth rate and reproduction performance get hampered (Pörtner and Knust 2007). Some fishes get mature faster in warm environments, so reproductive development starts in very small fishes, and somatic growth gets arrested. A higher mortality rate also is observed (Pauly 2010) in this condition.

2.3 Changes in Fish-Stock Distribution

Changing environment strongly affected the distribution of fish. Due to changes in ocean currents, the dispersal of larvae of different organisms living in the sea is getting affected. As the temperature of the ocean is increasing day by day, fishes start to migrate toward the area where the temperature is comfortable like poles or deep-water seas (Sumaila et al. 2011).

3 Impacts of Climate Change on the Livelihood

Changing climatic parameters reduce the production of fish and also affect both marine and freshwater species distribution. Furthermore, the poor communities dependent on fisheries or other agricultural activities for their livelihoods may face problems due to unavailability of fish or improper agricultural production (Shava and Gunhidzirai 2017). The livelihood of the population is at great risk as they are solely dependent on natural agricultural resources and have limited capacity to respond to a highly exposed climate change. India is the second-largest country with a middle-class population in the world (Rizal et al. 2017). Climate change reduces food production but the world's food demand is increasing day by day with the increase in population (Rizal and Anna 2019), so a sky-touching price may be paid for food in near future. Poor communities and small food producers get restricted to access food at a high price (FAO 2015) and this situation creates high food insecurity for the population especially women as they have restricted access to livelihood resources (human, social, financial, and natural) and also face constraints in accessing credit. Women generally can access 5–10 lower credits in comparison to their male colleagues (FAO 2011), and women in rural areas experience this more acutely than men as they are not given any power in decision making. According to FAO (2015), social differences also restrict people's access to information on weather and climate data. Indigenous peoples of different areas like a mountain, arctic low land, island, and coastal area choose to migrate, nationally or internationally, when they are unable to cope with the risks and challenges of climate change. Extreme weather conditions create an unsafe and risky situation for the community living in coastal or low-lying areas in particular. There are so many constraints faced by the people like reduction/stagnant of fish production as there is no proper information about advanced technology, access to rural finance schemes, limited infrastructure facility of fish culture, lack of fish markets, no income source other than farm, etc. which need to be addressed to influence the areas such as productivity, connectivity, and resilience.

4 Food Security

Food security is one of the basic human rights. Food security is a situation where all citizens can have access to sufficient, safe, and nutritious food physically or economically to achieve an active and healthy life by meeting their dietary needs (World Food Summit 1996; FAO 2003). Four dimensions that complete the concept of food security are availability, accessibility, stability, and utilization (Fig. 5).

We can term the situation food insecurity when any one of the problems affects the community (Béné et al. 2007). Fishing can act as a savior by enhancing food availability. Fisheries have the potential to provide economical security and nutritional security as fish is full of nutrients like protein, fat, vitamins, and minerals. Along with food production, climate change is degrading the quality of drinking water. Drinking water plays a vital role in our physiology, food digestion, and nutrient absorption. Food safety issues may be arisen due to climate change, especially foodborne diseases. There are direct consequences of climate change for food security:

- Shrinking the source of income.
- Decreasing the variety of aquatic organisms by disturbing the ecosystems both terrestrial and water (Inland, Coastal, and Marine).

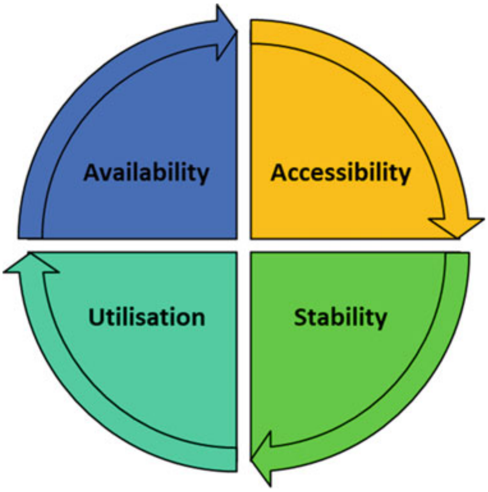


Fig. 5 Dimension of food security

- Breakdown of food systems and food security.
- Hampering the livelihood of rural people.

5 Policy for Sustainable Food Security

The key to achieving sustainable food security is to utilize domestic resources optimally (Rizal 2018). To achieve this government has to provide incentives to produce; enhance research activities; innovate in technologies; disseminate technologies among farmers holding small farms; and sustainable supply of staple food at reasonable prices and food safety (Rizal and Anna 2019). The modernized processing industry can play an important role in providing food security and access to the export market in a better way (Garibaldi 2012).

The following measures have to be implemented to realize the target of sustainable food security:

1. Adoption of a multisector approach to assuage the constraints which are affecting the poor, women, and other vulnerable groups to food security.
2. Expansion of partnerships and collaboration with different national, and international organizations, institutes/bodies/agencies. The private sector also is taken into count for sustainable food security.
3. Enhancement of fisheries by focusing on the core sector of fish production in a greater spectrum for coastal and rural development.
4. Increasing support for fisheries and marine research with longer-term research duration for specific and prioritized needs.
5. Strengthening of the community of practice (CoP) on fisheries and sustainable food and nutritional security by investing in collaborative learning and knowledge development work with external partners.

6 Activities to Increase the Resilience of Livelihoods

Social protection programs are essential which offer “safety nets” and “safety ropes” to the people. In this approach, mechanisms are to be provided for adopting opportunities and influencing abilities toward enhancing income generation (FAO 2015).

1. There must be management in fishing and fish-farming practices with changing species composition by introducing new or diversified species. The location of the farming may be changed.
2. Careful assessment and identification of adaptation practices may be done to avoid overexploitation of fisheries. There must be proper information about site selection, cage and pond construction, water quality management, integration of other activities with aquaculture, selection of species compatible with, selective

breeding, and incorporation of new and genetically improved species for diversified aquaculture which can help to spread risks.

3. Stakeholders in fisheries need to be supported financially in different investment activities such as mutualized finance scheme which helps in risk assessment and grows the ability for decisions making and action-taking.
4. Stakeholders need to be aware of weather and climate change. Information needs to be provided about weather observations, weather forecasts, climate projections, yield response models, environmental monitoring tools, and vulnerability assessments which can be helpful for them to assess the impact of weather and climate change on production. There should be the setup of weather updates and warning systems for vigilance (FAO 2015).
5. There is a requirement for changes in fishing practices, fish landing location, processing facilities, and plant location to avoid/overcome the extreme weather condition which may damage infrastructure, landing sites, post-harvest facilities, and transport routes. Extreme weather also affects water resources which may be problematic for aquaculture operations and other water-dependent activities.
6. There needs to be a change in livelihood strategies in which modification has to be done for instance with changes in fishers' migration patterns. Livelihood diversification is an alternative to cope with the changes in fishing activities especially in the coastal regions, inside and outside the fishery sector which may be a means of risk transfer.
7. Gender dimensions need to be reduced by involving women in different activities without any discrimination in resource access, and occupational change in areas such as markets, distribution, and processing where they can contribute significantly (FAO 2015).
8. Climate change potentially affects the fisheries (Barange and Perry 2009), so there is a need for fisheries conservation. The steps to conserve fisheries are reduction of stress on the already strained fishery resources, the adaptation of new fish species allowing to settle them successfully, and enhancement of adaptive capacity and resilience of fisher communities with new technologies.
9. Promote small-scale fisheries or artisanal fisheries businesses exploring the potential to develop their products and sell them to local, national, or International markets at good prices.
10. Suitable, economic, and environment-friendly mechanisms need to be adopted in fishing operations that efficiently lower running costs by reducing fuel consumption and increasing employment opportunities.
11. There should be a proper marketing channel, without the involvement of middlemen, to sell their products at landing sites (Ward and Jeffries 2000). Post-harvest loss and quality issues are also big challenges for fishers. The basic need for fish processing and transportation are infrastructure for establishing marketing space, cleaning of processing space, insulated storage and well-functionings transportation facilities, availability of potable water, ice and refrigeration system and proper roads etc.

7 Conclusion

Food security with good nutrition is the big challenge facing humankind in recent times as climate change is already undermining livelihoods. To mitigate climate change, there is a need for sustainable development by integrating governance strategies with scientific study, regulatory systems, and policy. The steps toward mitigation of climate change and food security will be the production of food with proper nutrition and abolishing hunger like national issues in the future. To achieve the goals modification of laws, regulations, and policies and interaction among governments, government agencies and stakeholders are very necessary.

References

Abram N et al (2019) IPCC special report on the ocean and cryosphere in a changing climate Ch. 1. Intergovernmental Panel on Climate Change (IPCC)

Barange M, Perry RI (2009) Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture. In: Cochrane K, De Young C, Soto D, Bahri T (eds) Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper No. 530. Rome, FAO. Available at ftp://ftp.fao.org/docrep/fao/012/i0994e/i0994e.pdf

Barange M et al (2018) Impacts of climate change on fisheries and aquaculture. Synthesis of current knowledge, adaptation and mitigation options. Food and Agriculture Organization of the United Nations

Béné C, MacFadyen G, Allison EH (2007) Increasing the contribution of small-scale fisheries to poverty alleviation and food security. Food and Agriculture Organisation, Rome

Bindoff NL et al (2013) Detection and attribution of climate change: from global to regional. Intergovernmental Panel on Climate Change (IPCC)

Cheng L et al (2020) Record-Setting Ocean warmth continued in 2019. Adv Atmos Sci 37:137–142

FAO (2003) Food security: conceptualising the linkages. Food and Agriculture Organisation of the United Nations, Rome

FAO (2005) Increasing the contribution of small-scale fisheries to poverty alleviation and food security. FAO Technical Guidelines for Responsible Fisheries. No. 10. FAO, Rome, p 79

FAO (2007) The state of world fisheries and aquaculture – 2006. Food and Agriculture Organisation of the United Nations, Rome, p 162

FAO (2011) The State of Food and Agriculture 2010–2011. Women in agriculture: closing the gender gap for development. Rome

FAO (2015) Climate change and food security: risks and responses. Food and Agriculture Organization of the United Nations

FAO (2017) The future of food and agriculture - trends and challenges. Food and Agriculture Organization of the United Nations

Francisco Blaha (2015) Climate change and fisheries. http://www.franciscoblaha.info/blog/2015/11/23/climate-change-and-fisheries. Accessed 9 June 2022

Frölicher TL, Laufkötter C (2018) Emerging risks from marine heat waves. Nat Commun 9:650

Garibaldi L (2012) The FAO global capture production database: a six-decade effort to catch the trend. Mar Policy 36:760–768

Kent G (1997) Fisheries, food security, and the poor. Food Policy 22(5):393–404

Pauly D (2010) Gasping fish and panting squids: oxygen, temperature and the growth of water-breathing animals. In: Kinne O (ed) Excellence in ecology series, vol 22. International Ecology Institute

Pörtner HO, Knust R (2007) Climate change affects marine fishes through the oxygen limitation of thermal tolerance. Science 315:95–97

Pörtner H-O et al (2019) IPCC special report on the ocean and cryosphere in a changing climate. Intergovernmental Panel on Climate Change (IPCC)

Rice JC, Garcia SM (2011) Fisheries, food security, climate change, and biodiversity: characteristics of the sector and perspectives on emerging issues. ICES J Mar Sci 68(6):1343–1353

Rizal A (2018) Science and policy in the coastal zone management. World News Nat Sci 21:1–8

Rizal A, Anna Z (2019) Climate change and its possible food security implications toward Indonesian marine and fisheries. World News Nat Sci 22:119–128

Rizal A, Suryana AAH, Herawati H, Lantun PD, Izza MA (2017) Regional perspective to build competitiveness for indonesian fishery sector in the global and autonomy regime. Int J Agric Env Res 3(6):4368–4388

Shava E, Gunhidzirai C (2017) Fish farming as an innovative strategy for promoting food security in drought risk regions of Zimbabwe. Jàmbá J Disast Risk Stud 9(1):1–10

Smale DA et al (2019) Marine heatwaves threaten global biodiversity and the provision of ecosystem services. Nat Clim Chang 9:306–312

Sumaila UR, Cheung WWL, Lam VWY, Pauly D, Herrick S (2011) Climate change impacts on the biophysics and economics of world fisheries. Nat Clim Chang 1:449–456

Thorpe A, Reid C, Anrooy RV, Brugere C, Becker D (2006) Poverty reduction strategy papers and the fisheries sector: an opportunity forgone? J Int Dev 18(4):489–517

Tiyo CE, Orach-Meza F, Edroma EL (2015) Understanding small-scale farmers' perception and adaption strategies to climate change impacts: evidence from two agro-ecological zones bordering National Parks of Uganda. J Agric Sci 7(10):253

United Nations (2017) No title. [WWW Document]. URL. http://www.un.org/sustainabledevelopment/blog/2017/06/world-population-projected-to-reach-9-8-billion-in-2050-and-11-2-billion-in-2100-says-un/. Accessed 11.9.17

Ward AR, Jeffries DJ (2000) A manual for assessing post-harvest fisheries losses. Natural Resources Institute, Chatham

World Food Summit (1996) Rome declaration on world food security. FAO, Rome

Nexus of Climate Change with Fish Production and Its Implications on Livelihood and Nutritional Security

Aparna Roy, Priya Chatterjee, and Basanta Kumar Das

Abstract

Fish being one of the major sources of protein and essential nutrients plays a crucial role in ensuring the nation's food security and also generates livelihood opportunities for a significant portion of the populace especially poor resource-limited marginal fishers often belonging to the vulnerable communities. Availability of an ideal aquatic environment is the limiting factor that regulates the outcomes from the sector as a result a changing climate poses serious multifaceted threats—both direct and indirect to this enterprise. Adaptation to these changes is required for both impact assessment and employing policies to minimize the impact. The impact of climate change on the socio-economics of the fishers is going to be area-specific and therefore specialized adaptation strategies and need-based capacity building are going to prove more fruitful rather than a generalized one, which accentuates the requirements of literature that provides an idea about the nature of changes, their possible impacts, and finally adapting strategies. This chapter highlights the impacts of the changes in climate on both the ecological and socio-economical aspects of fisheries and aquaculture and also directs towards possible adapting strategies that could be beneficial for policy making.

Keywords

Socio-economics · Policy · Livelihoods · Climate change

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1 Introduction

Fisheries and aquaculture have a huge impact on the Indian economy as well as on food security, nutritional security, employment generation, etc. The fisheries sector received a huge boon in the form of the blue revolution and witnessed a humongous growth in terms of production especially the move from marine-centered fisheries to inland-based fisheries as the contribution of the latter grew from a 36% in the 1980s to 70% in the recent times due to prioritization of culture-based fishery over capture-based fishery in the recent past. The fisheries sector is the primary source of livelihood for 20 million fishers in the nation and contributes approximately a staggering 1.75 trillion to the nation's economy. Aquaculture products being one of the major exporting goods in the country, fisheries also play a crucial role as it earns the nation an approximate amount of Rs. Forty-seven thousand crores in foreign currencies. Keeping these in mind it needs to be ensured that along with the expansion of this sector in the form of resource utilization and production enhancement, the preservation of resources to make sure prolonged sustained availability of these natural resources is also required.

While the emphasis is on enhanced fish production by adapting latest technologies and utilization of resources to their full potential the preservation of the aquatic ecosystem and prevention of degradation of the environment take a backseat. One of the major factors impacting the environment is climate change and since the fisheries and aquaculture depend largely on the availability of suitable habitats for the aquatic organisms, any derogatory changes in these habitats will have an impact on the health and availability of these fishes and ultimately impact on spawning season, migration pattern, survival, and mortality, selection of species to be firmed, etc. Primarily climate change will lead to frequent climatic events, increase in the water level, coastal and inland flooding, erratic drought patterns, altered salinity, and changes in riverbed level due to sedimentation which will eventually result in lower available water area ultimately causing habitat loss and degradation of aquatic ecosystems and would hamper fisheries practices. According to IPCC climate change will also change the pattern of disease outbreaks and may also change the susceptibility of the fishes towards various disease-causing agents. Recording the observable impacts of the changing weather patterns on the aquatic organisms is going to be crucial in adapting to these changes and taking mitigating measures.

2 Impact on Aquatic Ecosystems

Changes in the climate are being observed in rising water and atmospheric temperature, and changes in weather patterns especially in terms of precipitation are causing floods and drought which are eventually impacting aquatic habitats. Rising surface water temperature may result in lesser dissolved oxygen level, increased occurrence of disease and parasites, altering food web due to changes in competitor composition, may favor certain predators and invasive species to flourish in this altered

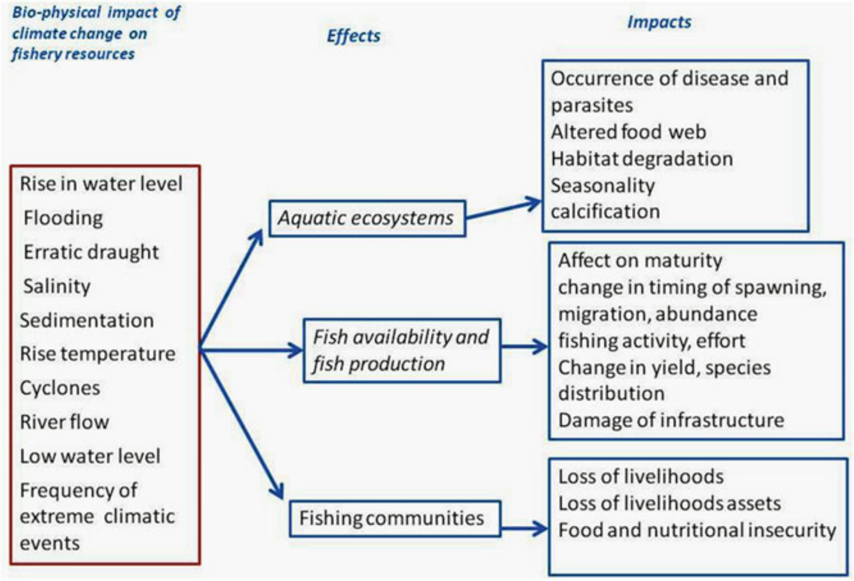

Fig. 1 Climate change impacts pathways in fisheries and aquaculture

environment, changes in plankton composition, etc. Higher inland water temperature will result in more stratification and less mixing of water due to changes in a temperature gradient, altered primary production hampering natural food supply for fish species, a shift in the ideal place and potential range for a particular species, etc. In higher altitude regions rising temperature will cause the melting of glaciers causing floods whereas in drier regions rivers and aquatic bodies may face scarcity of water due to erratic patterns of rainfall eventually leading to habitat loss. These ecosystem changes are likely to be reflected in the aquatic organisms and some of which can already be observed. Climate change impacts pathways in fisheries and aquaculture is depicted in Fig. 1.

3 Impact on Fish Availability and Fish Production

Changing rainfall as well as temperature is likely to affect the period of maturity; gonadal development in breeding seasons also causes transformation in physiology and sex ratio of fish species, change in spawning timing, migration, abundance, level of productivity, etc. The shift in the availability of fishes in a certain location, e.g., due to rising temperature in the upper stretches of Ganga, fish species which were earlier not captured in the upper stretch but the middle, can now be seen in the upper stretches as well. Increased acidity makes it difficult for zooplankton to form their shells through the process of calcification, which is likely to affect various aquatic food webs. Inland fishery is mostly dependent on rivers, riverine systems, and wetlands. Changes in hydrologic systems due to altered precipitation leading to changes in magnitude and frequency of flood would result in additional severe low flow due to improved evaporation and also change in peak stream from spring to winter season. The major river systems impacted by climate change are likely to be the Himalayan glacier-supported rivers like the Ganga, Brahmaputra, Indus, etc. which sustain the majority of fisheries activities of the nation. Also, the rivers originating from the mid-plateau of India like Narmada, Tapti, Mahanadi, Mahi, etc. will either face severe drought or excessive flood conditions. Precipitation along with the rate of downstream discharge regulates the water availability in the wetlands. Changes in river flow and water availability in the riparian zone would leave an impact on the overall fish production in these resources.

4 Impact on Fisheries and Aquaculture

Climate change is impacting fisheries through an all-encompassing varied range of pathways. The ecological and socio-economic impacts can have both direct and indirect impacts. The rising temperature and sea level directly influence the ecosystem, aquatic environment, fish stock, and productivity thereby affecting fishing activity, effort, livelihood, and management. The ecological factors will result in a change in production and productivity, species allocation, the unpredictability of catches, seasonal change in production, etc. The direct impact would be observed in damaged facilities and infrastructure, damaged crafts and gears, flood situations, and all of these have consequence effects on fisher folk communities, etc. Impact on socio-economics would result in migration of fishers in search of other jobs, poor health conditions, reduced social and economical security, limited resources for managing, fewer funds for an operation, etc.

5 Impact on Inland Fisheries

Inland fisheries have a substantial role both in livelihood generation and food security. Most of the countries involved in Inland fishery are developing countries where a section of the population depends on inland fisheries for income generation through small-scale fishery. Also, inland fisheries perform a crucial function in terms of food security in developing countries viz. India and Bangladesh where consumption of freshwater fishes as a part of the daily diet has been practiced throughout the ages. Worldwide the freshwater ecosystems supporting inland fisheries activities are subjected to various anthropogenic stressors like over-extraction of water whether for agricultural or industrial purposes, overutilization of resources, the inclusion of exotic species, contamination, habitat degradation, growing population pressure, etc. The impacts of climate change in combination with these already existing stressors will have severe effects on inland fisheries. Freshwater ecosystems are more susceptible to climate variability due to their low buffering capacity (Perry 2011). Water temperature, water flow, availability, etc. are physiological impacts on the ecological units that are sustaining inland fisheries. Freshwater fish species and many of the taxa they interact with are poikilotherms, i.e., thermal conformers and require specific temperature ranges that may differ between species and even life stages and are therefore affected by changes in water temperature at many levels including sub-organism, individual, population, species, community, and ecosystem levels (Brett 1970; Harrod 2016; Harrod et al. 2018; Souchon and Tissot 2012). Different species occupy distinct niches based on their food habit that is spread across different stratification layer within the aquatic habitat; any imbalance in these systems would result in the availability of these species. Among the anthropogenic stressors, the primary ones are river regulation, dam construction, water abstraction, etc. which cause degradation and fragmentation of habitat, loss of sensitive species, and population connectivity. Climate change affects catchment hydrodynamics through the change in the pattern of precipitation which affects discharge patterns and influences the availability of water for fisheries, physico-chemical parameters, etc. (De Wit and Stankiewicz 2006).

6 Impact on Biodiversity

Climate change may cause a reduction in the profusion of certain species while facilitating the growth of certain other species. Changes in species abundance will result in a change in harvesting patterns. On a larger scale, this may drive certain species towards extinction. Also, the incidence of invasion may become more random and certain alien species may become abundant in ecosystems that were otherwise not suitable for them. Changes in the top predators depend on prey availability. In case of an altered abundance of certain prey species, it will result in a lower encounter of prey densities by the predator. In a study conducted by Vass et al. (2009), it has been observed that the predator-to-prey ratio has decreased in the middle and lower parts of the river Ganga from 1:4.2 to 1:1.4 and 1:2.3 to 1:0.9, respectively, in the last four decade. Altered prey–predator relationships would disrupt the food chain and alter the availability of fish.

7 Impact on Fishing Communities

Indigenous communities who mostly depend on the fisheries and other agricultural practices for livelihood especially in the coastal and surrounding regions are likely to be hugely impacted as a rising sea level would leave them landless and also changing weather pattern leading to frequent cyclonic storms along with loss of mangrove covers not only causes destruction of their houses, properties, and livestock but also an influx of sea water in their ponds and freshwater bodies and agricultural lands leaves them unsuitable for fishing and farming thereby eliminating their sources of livelihood which ultimately forces them to move to towns and cities in search of jobs giving rise to climate refugees, an example of which can already be observed in the deltaic Sundarbans where rural landholders and pond owners were forced to move to towns and cities in the aftermath of the recent cyclonic storms like Ayla, Bulbul, and Amphan, and the dangers imposed by such unplanned migration were observed in the course of the nation-wide lockdown due to the Covid-19 pandemic where migrants could not sustain their daily lives in the absence of their livelihood giving the situation an apocalyptic appearance. In the case of communities living in various areas of the mainland, they exclusively rely on traditional knowledge and indigenous practices. In changing climatic conditions leading to reproductive and behavioral changes in the aquatic organisms these people are likely to face serious constraints in terms of fisheries and therefore are expected to face loss of livelihood eventually crippling them with poverty and malnutrition.

7.1 Loss of Livelihood

Fish Seed collection is one of the major livelihood options of the fishermen community in Sundarbans. But, due to the impact of climate change, particularly for fluctuation in surface water salinity, and sea-level rise the availability of commercially important shellfish and finfish has reduced, and it is now directly impacting their major livelihood option.

In Sundarbans, people are involved in fish culture in the adjoining ponds of their houses for consumption purposes and also for earning. But, due to climatic hazards, like changes in rainfall patterns or for prolonging dry spells the ponds are dried up and the aquaculture activities often hamper and the food and nutritional security comes under question.

Capturing/harvesting fish from the water channels, canals, paddy fields, and creeks is often hampered due to floods or prolonged dry spells. The creeks, channels, and canals are overflowing or dried up and the fishermen's community loses their earnings.

7.2 Impact on Food and Nutritional Insecurity

"Adequate access of food to all people at all times for an active, healthy life" is food security (Gross et al. 2000). People should have availability and access to safe and quality drinking water and also nutrition-rich food to meet their daily dietetic requirements. But, due to climate change, some islands are almost disappearing, some are sinking, agricultural land is shrinking, and many people are displaced from their land. Due to the ingress of sea water in some places, people do not have even physical access to safe drinking water. Moreover, due to extreme climate event Aila in 2009, in Indian Sundarbans, the salt water ingress has destroyed the natural habitat of many nutrition-rich Small Indigenous Fishes (SIFs) like Kholisa, *Nandos,* Akash Tangra (*Mystus vittatus*), Pabda (*Ompok pabda*), etc. and that has caused a drastic reduction of the population of such fishes in the freshwater bodies in Sundarbans (Sinha et al. 2014). Small Indigenous Fishes are traditionally an integral part of the household diet of Indian Sundarbans. These small fishes are rich in vitamins and minerals. Women of the fisher folk community are solely responsible for the household food and nutritional security because they collect food, prepare food, purchase food, grow food, and store food. Due to climate change, the decline in SIFs in natural water bodies ultimately has led to nutritional insecurity of the local populace of Sundarbans, as fish is the only source of protein, minerals, and vitamins to the fishermen community. Moreover, due to land erosion, and an increase in soil and water salinity, kitchen gardening is also not clicking. So, people of the fisher folk community have to think of alternate strategies to feed their children. They are compelled to work hard or overtime to earn money.

8 Vulnerability and Resilience

Vulnerability and resilience have come to be known as two key concepts in the climate change scenario. Vulnerability is defined as the susceptibility of groups or individuals due to climate changes. Vulnerability is influenced by key factors like external environmental threats, internal factors like socio-economic disposition, governance, geographical distribution, food security, conflict, quality of health, etc.; according to the Intergovernmental Panel on Climate Change vulnerability is defined as "...a function of the character, magnitude, and rate of climatic variation to which a system is exposed, its sensitivity, and its adaptive capacity" (McCarthy et al. 2001: p. 995). Allison et al. (2005) described vulnerability (V) as a function of potential impact (PI) which is the total impact without taking any planned adaptation into account and adaptive capacity (AC) which is the ability of systems to adapt to changing climate, i.e., $V = f(\text{PI, AC})$, where PI is determined by exposure (E) and sensitivity (S) and E is the degree to which fisheries systems are exposed to climate change; and S is the degree to which economy reliant on fisheries is sensitive to changes.

Resilience depends on vulnerability and adaptive capacity. In fisheries-like sectors where management involves both social-ecological systems resilience has gained acceptability. Resilience focuses on the capacity of the system to defy change and also involves the importance of disturbance, reform, and restoration. Social economical resilience includes social learning, information, awareness, leadership, social networks, linkages, and institutions for navigating disturbance, adapting to change, and managing the resilience of a system to remain in a desirable state (Folke 2006).

9 Adaptation and Mitigation of the Impacts of Climate Change

Ideally controlling the emission of greenhouse gases and other damaging practices that accelerate global warming therefore climate change should have been the priority to lower the chances of worsening the situation than it already is; unfortunately, it seems to be a matter of conflict among the decision-makers at an international level, thus making it nearly impossible to achieve the climate goals in its due time. Hence the next course of action is going to be making adjustments and adapting to the changing environment. Detailed and systematic analysis of the presently available data is going to be crucial in assessing the observed changes and predicting the expected changes in the future and therefore recruiting strategies to address the challenges.

Adaptation involves multifaceted adjustments by people to sustain their well-being which includes ecological, social, and economic areas, either in the face of an already observed change or in anticipation of one that is predicted to take place soon. Therefore adaptation can be either in terms of bringing changes in fisheries management practices or through building adaptive capacity (Daw et al. 2009). Therefore adaptation can be defined as ongoing changes involving actions, decision making, planning strategies, and attitudes towards capitalizing and alleviating the unfavorable effects of climate change.

10 Adaptation in Fisheries Management

The role of management in fisheries is mostly limited to achieving the highest production through sustainable practices that involve static management plans that do not generally incorporate environmental processes. In the face of a changing climate introducing somehow flexible management practices that are specific to the requirement at the moment is going to be crucial. Therefore adopting the ecosystem approach to fisheries (EAF) (FAO 2007), which involves an ecosystem-integrated and participatory approach, is going to prove more beneficial. The act of strategizing adaptive management practices, making policies following those decisions, developing new technologies, and proper implementation of these newly adapted tools and strategies is going to be crucial at the institutional level. At the same time involvement of smaller organizations like district or block level fishery officials, fishers cooperatives, panchayat members, and even individuals is imperative in ensuring successful adaptation of these practices through area-based micro-management and needs to be equally valued to ensure that policies enforced by larger institutions are equally effective at the local level and are adaptable by the local communities.

11 Building Adaptive Capacity

The consequences of climate change are unprecedented; hence the fishers especially rural, marginal fishers who are likely to be otherwise less sensitized would probably find it difficult to make the necessary adjustments that are being made in the face of such changes. To address this issue capacity building is going to be of utmost importance. Capacity-building programs that are directed towards enabling them for making any adjustments when necessary and allocating adequate funds for the same would prove to be beneficial in this scenario. Also, the institutional framework needs to be built keeping in mind the need for shifting focus towards adapting flexible resilient fishery practices in place of the static production centric one. The resource-poor fishers are already troubled with various constraints be it socio-economical, health, etc. that leave them more vulnerable to adversities brought upon by the changing climate. Therefore any capacity-building work done with the aim of their general well-being would ultimately be beneficial in empowering them with adaptive abilities.

12 Adaptation in Aquaculture Practices

Adapting from the categories provided by Tompkins and Adger (2004), Smit et al. (2000), and Daw et al. (2009) provided certain adaptation strategies for aquaculture involving both public and private involvements that can be either anticipatory or reactive based on the kind of impact a certain change asserts on fisheries. Adaptations in aquaculture practices need to be made as per the circumstances are faced. In case of reduced productivity accessing higher-value markets by the traders and increasing fishing efforts by fishers can be beneficial. In case of increased variability in yield introducing insurance schemes would benefit the smaller farmers whereas the application of integrated adapting measures in terms of fishing practices can help secure the amount of yield. In case of change in the distribution of fisheries research predicting the availability of fish stock would prove to be beneficial, especially for riverine fisheries. In case of reduced profitability through fisheries reducing the cost to increase efficiency is required and alternate livelihood opportunities need to be considered when cost reduction cannot be implemented or the workforce needs to be reduced. Also in more severe cases leaving the fishery altogether for other livelihoods has to be advised. As the coastal, riparian, and the communities of the floodplain wetlands are more vulnerable to the changing climate reactive and anticipatory adaptations are required. Early warning systems and educating the common populace about the coming dangers help to mitigate the adversities to some extent. Improving infrastructure to secure landing sites or equipment would reduce loss. Post-disaster responses like quick disaster response and rehabilitation would save potential live loss, and assisted migration when necessary would ensure minimal damage in terms of overcrowding and acquiring unhealthy living situations. Diversification of markets and products and also dispersal of information on the trends and anticipation in terms of market shock would help to avert the economic shocks and would also help fishers to reach international markets and achieve a fair price for their produce (FAO 2007). While generalized adaptation measures are introduced Morton (2007) argues that it would be difficult to predict the impacts of climate change and therefore come up with a model for adaptation to these changes, especially for small and marginal farmers. Hence location and context-specific adaptation strategies would prove to be more beneficial. Eriksen et al. (2005) encourage diversifying cropping systems and also the use of wild foods.

13 Gender Aspect to Vulnerability and Adaptive Capacity

Earlier studies have revealed that access to basics is essential for adaptive capacity depending on various socio-economic variables like age, class, gender, etc. (Cutter 1995; Denton 2004; Enarson 2002). Consequently, climate change also has gender-specific propositions (Dankelman 2002). There are defined gender roles in social, cultural, and household life that affect the vulnerability and adaptive capacity of women to climate change. According to Davison (1988), women in developing countries are involved in natural resource-based activities like agriculture compared to salaried jobs and since these resources are directly dependent on climatic conditions women are likely to be affected through different mechanisms like water availability, availability of fuelwood, vegetation, health issues, etc. Women are seen to be the worse sufferers of any natural disaster whether in terms of more death or post-event recovery which can be attributed to the additional burden of caregiving to children and the elderly compared to men who return to their pre-disaster roles. The vulnerability of women is amplified by unequal access and right over resources, discrimination in property rights, etc. Like other agricultural practices, women's involvement in fisheries is also affected by similar constraints. Though the involvement of women in large-scale fish capture is less observed, women are more involved in catching fish especially SIFs for household consumption which is crucial for household nutritional security thus in case of altered fish availability due to climate change it is going to add to the burden of hunger and malnutrition. The role of gender in influencing adaptive capacity is critical and thus capacity-building policies implemented without considering gender add the gender dimension of vulnerability (Denton 2004). It can be also observed that proactive capacity building rather than reactive disaster management would be beneficial in ensuring gender equality (Mirza 2003).

The fisherwomen perceived that in any governmental program they are generally ignored, and no input facilities are provided to them even after heavy climatic shock. Domination of individuals or a particular group often causes an equilibrium in distributing inputs. In inland open water fisheries there is no insurance policy for the fishermen's communities. Due to a lack of financial inclusion, the fishermen's community cannot access insurance facilities due to damages in natural calamities. Even they cannot access institutional credit facilities after smash-up events. Male members generally migrate for a job and the fisherwomen stay behind and become more vulnerable to criminal attacks or sexual violence. The health and hygiene of fisherwomen are often forfeited at the cost of their family responsibilities.

14 Mitigation

Though emission from fisheries especially inland fisheries is not generally significant, however opportunities to reduce emissions if possible need to be explored. The use of fossil fuel in vessels, emission of GHGs while production of fish feeds, and emissions due to trade are the major contributors to this sector. Improving the efficiency of fishing vessels to ensure lesser use of fuels or sustainable practices in feed production or fisheries management or encouraging local consumption or use of bulk sea freight for transport of aquaculture products in place of using air freights may help reduce overall emission. Long-term goals may include increasing mangrove cover, research on climate-resilient species, etc.

15 Conclusion

Climate change will impact the weather systems and therefore it will affect weather patterns, the occurrence of climatic events that would ultimately impact fisheries resources, and therefore fisheries practices and all the associated areas. Adaptation strategies that have been devised to combat climate change sometimes cannot be implemented properly due to a lack of political will. It can be argued that the adaptation that involves large-scale investment or major action is more likely to be implemented when triggered by an extreme event. It can also be noted that adaptation operates differently at different spatial and socio-economical levels and therefore the feasibility of a certain adaptation plan needs to be assessed separately for each condition. For management practices, comprehensive and ecosystem-integrated approaches are to be encouraged. Vulnerability and risk assessment needs to be conducted at the local level. The threat to food security needs to be assessed beforehand, and availability of the required nutrition needs to be ensured to avert the impact of hunger and malnutrition and the consequential morbidities on the society. Water demand is likely to increase in the coming years due to uncertainty involving water availability and growing population pressure, increased need for irrigation in agriculture, etc. which will lead to water stress. To deal with it integrated water resource management practices and different measures for different resources need to be implemented. Reforms in institutional, market infrastructure, and fisheries governance to adjust and adapt to the changing environment are required. Finally, extensive research and development of technologies, both to assess and adapt to the ongoing changes, seem to be the best choice of defense.

References

Allison EH, Adger WN, Badjeck M-C, Brown K, Conway D, Dulvy NK, Halls A, Perry A, Reynolds JD (2005) Effects of climate change on the sustainability of capture and enhancement fisheries important to the poor: analysis of the vulnerability and adaptability of fisher folk living in poverty. Fisheries Management Science Programme MRAG/DFID, London, Project no. R4778J. Final technical report. 164 pp

Brett JR (1970) Environmental factors, part I. temperature. In: Kinne O (ed) Marine ecology. London, Wiley, pp 515–560

Cutter SL (1995) The forgotten casualties: women, children, and environmental change. Global Environ Chang 5:181–194

Dankelman I (2002) Climate change: learning from gender analysis and women's experiences of organising for sustainable development. Gender Dev 10:21–29

Davison J (ed) (1988) Agriculture, women, and land: the African experience, 1st edn. Routledge. https://doi.org/10.4324/9780429044045

Daw T, Adger WN, Brown K, Badjeck M-C (2009) Climate change and capture fisheries: potential impacts, adaptation and mitigation. In: Cochrane K, De Young C, Soto D, Bahri T (eds) Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper. No. 530. FAO, Rome, pp 107–150

De Wit M, Stankiewicz J (2006) Changes in surface water supply across Africa with predicted climate change. Science 311(5769):1917–1921. https://doi.org/10.1126/science.1119929

Denton F (2004) Gender and climate change—giving the "latecomer" a head start. IDS Bull 35:42–49

Enarson E (2002) Gender issues in natural disasters: talking points and research needs. Crisis Women Other Gend Concerns:5–12

Eriksen S, Brown K, Kelly PM (2005) The dynamics of vulnerability: locating coping strategies in Kenya and Tanzania. Geogr J 171:287–305

FAO (2007) Information and communication technologies benefit fishing communities. New directions in fisheries—a series of policy briefs on development issues, 09. FAO, Rome, 16p

Folke C (2006) Resilience: the emergence of a perspective for social-ecological systems analysis. Global Environ Change 16:253–267

Gross R, Schoeneberger H, Pfeifer H, Preuss HJ (2000) The four dimensions of food and nutrition security: definitions and concepts. Scn news 20(20):20–25

Harrod C (2016) Climate change and freshwater fisheries. In: Craig JF (ed) Freshwater fisheries ecology. John Wiley & Sons, Ltd, Chichester, pp 641–694. https://doi.org/10.1002/9781118394380.ch50

Harrod C, Ramírez A, Valbo-Jørgensen J, Funge-Smith S (2018) How climate change impacts inland fisheries. In: Impacts of climate change on fisheries and aquaculture, p 375

McCarthy J, Canziani OS, Leary N, Dokken D, White K (2001) Climate change 2001: impacts, adaptation and vulnerability. Cambridge University Press, Cambridge

Mirza MMQ (2003) Climate change and extreme weather events: can developing countries adapt? Clim Pol 3:233–248

Morton JF (2007) The impact of climate change on smallholder and subsistence agriculture. Proc Natl Acad Sci 104:19680–19685

Perry RI (2011) Potential impacts of climate change on marine wild capture fisheries: an update. J Agric Sci 149(S1):63–75

Sinha A, Das SK, Roy A, Mitra A, Mukherjee CN, Sengupta A (2014) Small indigenous fish an alternate source to improve rural livelihood and nutritional security in coastal zone of Sunderbans, India. In: Extended abstract of national conference on mitigation and adaptation strategies in wetlands—a community leadership perspective, pp 73–74

Smit B, Burton I, Klein RJT, Wandel J (2000) An anatomy of adaptation to climate change and variability. Clim Change 45:223–251

Souchon Y, Tissot L (2012) Synthesis of thermal tolerances of the common freshwater fish species in large western Europe rivers. Knowl Manage Aquat Ecosyst 405.: Art:03, 48 pp. https://doi.org/10.1051/kmae/2012008

Tompkins EL, Adger WN (2004) Does adaptive management of natural resources enhance resilience to climate change? Ecol Soc 9(2):10

Vass KK, Das MK, Srivastava PK, Dey S (2009) Assessing the impact of climate change on inland fisheries in River Ganga and its plains in India. Aquat Ecosyst Health Manage 12(2):138–151. https://doi.org/10.1080/14634980902908746

Part II

Adaptation in Fish Digestive Physiology and Biochemistry Under Changing Environment

Gut Microbes and Its Physiological Role in Fish: Adaptive Strategies for Climatic Variability

Kavita Kumari and Sangeetha M. Nair

Abstract

The gut microbes of fish encompass various effects on the host such as the size of the fish, their metabolism, food, feeding behavior, and immunity. The process is mediated through interaction between microbes and the gut-brain axis. In fish larvae, the microbes are introduced from the egg, surrounding water, and their first feed. However, there is species-specific variation in the colonization of microbial communities. The microbial composition of the gut varies; some dominant microbes are Proteobacteria, Firmicutes, Bacteroidetes, Actinobacteria, and Fusobacteria. The various environmental, ecological, and evolutionary factors affect intestinal microbial communities and their functions. Various intrinsic factors also influence the gut microbes such as phylogeny, sexual state, life stages, trophic status, and genetics. The gut microbial community modulates the host's physiology and the host provides nutrients to the gut microbes. The gut microbial activity depends on the composition and the diversity of gut microbes. The feeding, digestion, and metabolism of the host can be affected by gut microbes. In addition, it also influences stress response, reproduction, development, and immune response. Food and feeding alteration can change the gut microbial community. The inclusion of different proteins, lipids, probiotics, prebiotics, etc. can alter the gut microbes and enhance the health status.

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Intestinal microbes · Feeding · Probiotics · Prebiotic · Immunity · Growth · Fish

1 Introduction

Microbes are different microorganisms, present in the environment. Microbiome refers to the characteristic microbial community inhabiting a well-defined habitat with distinct physicochemical parameters (Whipps et al. 1988*)*. Microbes are ubiquitous and present across all life-sustaining habitats on Earth; the differences exist in the varied environment which carries different microbial communities. Microbes are not only present in these external environments, but they are also found to be associated with many eukaryotic hosts (Sullam et al. 2012). The impact of microbial communities on the health of various types of the host such as plants, fish, and terrestrial animals including humans has gained wide attention nowadays (Brugman et al. 2018). The microbiota can offer various benefits to the host by supplementing adequate nutrients, inducing host immune development and metabolism, and protecting the host against invading pathogens (Brugman et al. 2018). Vertebrates' gastrointestinal (GI) tract is a composite microbial ecosystem containing a complex and dynamic association of microorganisms, which have crucial roles in the nutrition and health of the host (Wang et al. 2018). The various environmental factors influence the microbial community composition; at the same time microbes also influence the host environment (Bletz et al. 2017).

2 Gut Microbiota

Gut microbiomes are the microbes present in the intestine. The gut microbiomes of fish encompass various effects on the host such as the overall size of fish, their metabolism, food and feeding behavior, and their immunity (Yukgehnaish et al. 2020). The gut microbes are dynamic. These microbiomes are either transient or persistent, depending on the duration they live in the gut microbiota (Prasanth et al. 2018). The persistent microbiota lives in association with the gut wall and has a symbiont relationship with the host (Zhang et al. 2016). The transient microbiota comes through external sources such as food and does not live for a longer period in the stomach (Yukgehnaish et al. 2020).

3 Origin and Sources of Gut Microbes

Various factors control the gut microbial content of an infant. In fishes, the origin of gut microbes is still in the infant stage. In humans, it has been suggested that the gut microbes might have been introduced through the birth canal, pass through the oral cavity to the placenta, or subsequently introduced through the gastrointestinal tract in infants during breastfeeding (Prince et al. 2014; Gueimonde et al. 2006). In fish larvae, the entrance of microbes occurs from the egg, the adjacent water, and their initial feed (Egerton et al. 2018). However, there is species-specific variation in the colonization of microbial communities (Egerton et al. 2018). The species-specific variation in the microbial community in the larvae represents the variation of egg glycoprotein (Larsen 2014). The variation of these microbes depends on the variation of the surrounding environment from where the microbes are being attached to the egg surface. The chorion-attached bacteria subsequently colonize the gut of the newly developed larvae (Larsen 2014). The colonization of bacteria further diversifies when the larvae take the water from the environment (Lauzon et al. 2010). The feeding habit of fish also influences their microbial diversity and changes as the larvae develop into fry, fingerling, and adults (Ringø and Birkbeck 1999; Egerton et al. 2018). It has been observed that this microbial population becomes stable within the first 50 days in various species (Larsen 2014).

4 Diversity of Gut Microbes

The variability is one of the remarkable features of GI microbiota in fishes. It is not yet fully understood the complex process involved in the regulations of these bacterial populations in the GI tract of fish. Few studies have been focused on fishes such as Rainbow trout, Common carp, Atlantic cod, Atlantic salmon, Grass carp, and Zebrafish (Wang et al. 2018). The microbial composition of the gut varies although some dominant microbes are Actinobacteria, Bacteroidetes, Firmicutes, Fusobacteria, and Proteobacteria (Eichmiller et al. 2016). The various environmental, ecological, and evolutionary factors affect intestinal microbial communities and their functions. Various intrinsic factors also influence the gut microbes such as phylogeny, sexual state, life stage, trophic status, and genetics (Egerton et al. 2018). Closely related mammals having similar diets are found to harbor similar gut microbes (Sullam et al. 2012). The diversity of gut microbes also varies between fish species and within fish species. The composition of gut bacteria in fishes can be determined by the habitat, trophic level, and possibly host phylogeny shape (Sullam et al. 2012). Various research proved that the microbial flora composition varies (Table 1) in different fish species owing to their nutrition, intestinal microenvironment, age, geography, environmental factors, stress, etc. (Verschuere et al. 2000; Skrodenyte-Arbaciauskiene et al. 2008). The variation of gut microbiota depends up on the type of fish species and environmental conditions such as developmental stage of fish, feeding regime, seasonal variation, temperature, pH, nutrients intake, captive sate, and sexual state which allows the host to perform different functions and enables the host to thrive in various conditions (Hansen and Olafsen 1999; Dhanasiri et al. 2011; Hovda et al. 2012; Miyake et al. 2015; Apajalahti 2005; Cordero et al. 2015). The most influencing factor to affect the diversity of fish is trophic status, habitat of the fish, and host ancestry (Sullam et al. 2012).

Table 1 Microbial diversity in different fish species

Fish species	Dominant bacteria	References
Freshwater		
Salmo trutta fario	Aeromonas, *Buttiauxella agrestis*, *Budvicia aquatica*, *Erwinia persicinus*, *Obesumbacterium proteus*	Skrodenyte-Arbaciauskiene et al. (2006)
Onchorhyncus mykiss	Proteobacteria, Actinobacteria, Fusobacteria	Navarrete et al. (2012)
	Bacteroidetes, Fusobacteria, Proteobacteria, Firmicutes, and Actinobacteria	Michl et al. (2017)
	Tenericutes, Firmicutes, Proteobacteria, Bacteroidetes	Lyons et al. (2017)
Silurus meridionalis	Tenericutes, Fusobacteria, Proteobacteria, and Bacteroidetes	Zhang et al. (2018)
Aristichthys nobilis	Firmicutes, Methylocaldum, and Bacillus	Zeng et al. (2020)
Hypophthalmichthys molitrix	Cyanobacteria, Proteobacteria, Actinobacteria, Bacteroidetes	Ye et al. (2014)
	Anaerospora	Zeng et al. (2020)
Danio rerio	Aeromonas, Pseudomonas	Bates et al. (2006)
	Lactobacillus plantarum, *Lactobacillus fermentum*	Russo et al. (2015)
	Planctomycetes, Fusobacteria, Verrucomicrobia	Koo et al. (2017)
Ctenopharyngodon idella	Proteobacteria, Firmicutes, Actinobacteria	Han et al. (2010)
	Proteobacteria and Cyanobacteria	Zeng et al. (2020)
Gambusia affinis	Proteobacteria and Flavobacteria	Carlson et al. (2017)
Carassius auratus	Fusobacteria, Proteobacteria, Bacteriodetes	Li et al. (2017)
	Firmicutes, Methylocaldum, and Bacillus	Zeng et al. (2020)
Silurus asotus	Aeromonas, Flavobacterium, Bacteroides, Pseudomonas	Di Maiuta et al. (2013)
Lagodon rhomboides	Clostridium, Mycoplasma, Photobacterium	Ransom (2008)
Oreochromis niloticus	Firmicutes, Actinobacteria, Proteobacteria	Zhai et al. (2017)
Morone saxatilis	Aeromonas, Pseudomonas, Vibrio	MacFarlane et al. (1986)
Paralichthys lethostigma	Clostridium, Photobacterium	Givens et al. (2015)
Salmo salar	*Acinetobacter junii*, Mycoplasma, Lactobacillus	Holben et al. (2002)
	Escherichia, Propionibacterium	Green et al. (2013)
Acipenser baerii	*Cetobacterium somerae*	Geraylou et al. (2013)
Morone saxatilis	Aeromonas, Pseudomonas, Vibrio	MacFarlane et al. (1986)
Ictalurus punctatus	Bacteroidetes, Firmicutes, Fusobacteria, Proteobacteria	Gatesoupe et al. (2016)
Astyanax mexicanus	Gammaproteobacteria, Firmicutes, Bacteroidetes, and Betaproteobacteria	Ornelas-García et al. (2018)

(continued)

Table 1 (continued)

Fish species	Dominant bacteria	References
Marine water		
Odax pullus	Clostridium, *Eubacterium desmolans*, Papillibacter	Clements et al. (2007)
Sardinella longiceps	Achromobacter, Vibrio, Pseudomonas	Karthiayani and Mahadeva Iyer (1967)
Scomber scombrus	Psychrobacter, Vibrio, Shewanella	Svanevik and Lunestad (2011)
Trematomus bernacchii,	Proteobacteria, Actinobacteria, Firmicutes, Thermi, Bacteroidetes Tenericutes	Yan et al. (2016)
Gadus morhua	Aeromonas, Cytophaga, Pseudomonas, Lactobacillus	Strøm and Ringø (1993)
Gillichthys mirabilis	Mycoplasma	Bano et al. (2007)
Clupea harengus	Flavobacterium, Pseudomonas	Hansen et al. (1992)
	Psychrobacter, Alteromonas	Curson et al. (2010)
Syngnathus scovelli	Proteobacteria	Ransom (2008)
Chanos chanos	Vibrio, Pseudomonas	Fernandez et al. (1996)
Dicentrarchus labrax	Moraxella, Vibrio, Acinetobacter	Gatesoupe et al. (1997)
	Proteobacteria, Bacteroidetes, Actinobacteria, Firmicutes	Gajardo et al. (2017)
Sparus aurata	Pseudomonas	Floris et al. (2013)
Hippoglossus hippoglossus	*Photobacterium phosphoreum* (adults)	Verner-Jeffreys et al. (2003)
Pagrus major	Cytophaga, Aeromonas, Pseudomonas, Vibrio	Muroga et al. (1987)
Hermosilla azurea	Faecalibacterium, Enterovibrio, Bacteroides, Desulfovibrio	Fidopiastis et al. (2006)
Solea solea	Moraxella, Pseudomonas, Flavobacterium	Campbell and Buswell (1983)
Scophthalmus maximus	*Vibrio alginolyticus*, *Vibrio anguillarum*, *Vibrio harveyii*, Pseudomonas, Acinetobacter	Munro et al. (1994)
	Vibrio, Acinetobacter, Moraxello	Gatesoupe et al. (1997)
Sebastes schlegeli	Acinetobacter, *V. alginolyticus*, *V. anguillarum*, Pseudomonas	Tanasomwang and Muroga (1989)
Acanthopagrus schlegeli	Aeromonas, Pseudomonas, Vibrio	Muroga et al. (1987)
Cynoscion nebulosus	*Escherichia coli*	Ransom (2008)

(continued)

Table 1 (continued)

Fish species	Dominant bacteria	References
Gadus morhua	Pseudoalteromonas, Microbacterium, Roseobacter	Reid et al. (2009), Aschfalk and Muller (2002)
	Clostridium perfringens, *Vibrio* sp.	Star et al. (2013)
Sciaenops ocellatus	Cetobacterium, Vibrio, Photobacterium	Ransom (2008), Givens et al. (2015)
Paralichthys lethostigma	Clostridium, Photobacterium	Ransom (2008), Givens et al. (2015)
Acanthurus sp.	Epulopiscium	Miyake et al. (2015)
Pomatomus saltatrix	*Vibrio* sp., Pseudomonas	Newman et al. (1972)
Notothenia coriiceps, Chaenocephalus aceratus	*Vibrio* sp., Photobacterium	Ward et al. (2009)
Solea senegalensis	*Vibrio ichthyoenteri*	Martin-Antonio et al. (2007)
Kyphosus sydneyanus	*Clostridium* sp.	Moran et al. (2005)
Salmo trutta trutta	*Aeromonas sobria*, Pseudomonas	Skrodenyte-Arbačiauskiene et al. (2008)
Fugu niphobles	Flavobacterium, Vibrio, Pseudomonas	Sugita et al. (1989)
Plecoglossus altivelis	Gammaproteobacteria, Alphaproteobacteria, Firmicutes, and Bacteroides	Nie et al. (2017)
Andamia tetradactylus	Spirochaetes and Tenericutes	Yoshida et al. (2022)
Reef associated		
Acanthurus nigricans, Chlorurus sordidus, Lutjanus bohar	Proteobacterium, *Vibrio ponticus*, *Vibrio fortis*	Smriga et al. (2010)
Aplodactylus arctidens	Clostridium, *Eubacterium desmolans*, Papillibacter	Clements et al. (2007)
Epinephelus coioides	Pseudomonas, Bacillus, Acinetobacter, Vibrio	Sun et al. (2009)
Pomacentrus moluccensis	*Vibrio harveyi*, Shewanella, Endozoicomonas	Parris et al. (2016)
P. amboinensis		
P. wardii		
P. bankanensis		
P. nagasakiensis		
P. chrysurus		
Siganus fuscescens	Proteobacteria, Cyanobacteria, and Firmicutes	Nielsen et al. (2017)

4.1 Trophic Level

The gut microbes of the fishes change with the trophic status of the fish and correlate it with the availability of natural food and their feeding behavior (Liu et al. 2016). The understanding of fish gut microbiota and their role in the digestion of food is vital (Wang et al. 2018). This will help to accelerate the digestion and health of fish for the culture of various fish species. Various studies have been done to find the gut microbial composition of fish with different feeding habits (Givens et al. 2015). It has been found that the gut microbial content of herbivores is distinct from carnivorous fish (Liu et al. 2016). The planktivorous and benthivorous showed unique microbial content for different fish species in their gut (Uchii et al. 2006). However, the bacterial diversity is found lesser in carnivores, and gradually increases in omnivores and herbivores (Wang et al. 2018). The gut microbiota varies with species belonging to the same trophic level as observed in herbivorous fishes like silver carp, bighead, and grass carp (Li et al. 2018).

The digestive tract of herbivorous fish harbors anaerobic bacteria of the phylum Firmicutes and class Clostridia (Mouchet et al. 2012). The dominance of Firmicutes in the gastrointestinal tract has been observed in many fish species (Clements et al. 2007; Miyake et al. 2015). The microbes repeatedly occur in omnivores, planktivores, and carnivores are Aeromonas, Pseudomonas, and Vibrionaceae (Egerton et al. 2018). The microbes such as *Pseudomonas* spp., Aeromonas, and *Photobacterium* spp. produce digestive enzymes such as proteases and chitinases which help in digestion (MacDonald et al. 1986; Itoi et al. 2006). However, the diversity of these microbes varies with habitat, season, feeding and sex, and age.

4.2 Genetic and Sex of the Host

The composition of microbes varies within and between species. The interspecies variation in gut microbial diversity has been observed for snout bream, bighead carp, grass carp, and silver carp (Li et al. 2018). The variation in gut microbes between sex has also been observed for stickleback (*Gasterosteus aculeatus*), which might be due to sex-specific microbial interaction of feed variation (Bolnick et al. 2014). But only a few studies prevail in the area and its mechanism is poorly understood.

However, among the genetics and environment, the environment has more influence on the diet composition of fishes. It has been observed that different fish species (Channel catfish and blue catfish) even in the same environmental condition may harbor the same gut microbial content (Lokesh et al. 2018).

4.3 Age of the Fish

The microbial diversity changes with the age of fish. The reason might be due to the diet variation and hormonal changes in different life stages of fish (Cantas et al. 2012). The gut microbial diversity is increased with age in catfishes (Zhang et al.

2018). In Atlantic salmon also gut microbes vary between embryo and hatchlings, and hatchings exhibited more microbial diversity (Lokesh et al. 2018).

4.4 Season

The diversity and abundance of gut microbes change with the season (Hagi et al. 2004; Sullam et al. 2012). The variation might be for a short duration or a longer period. The seasonal variation in gut microbes might have influenced due to temperature variation or due to changes in food composition in the gut (Al-Harbi and Uddin 2004). The dominant taxa vary with season (Hagi et al. 2004), and the count of total bacteria peaks during summer and autumn (Macmillan and Santucci 1990; Al-Harbi and Uddin 2004). However Neuman et al. (2016) could not find any relationship between season and change in gut microbial diversity.

4.5 Habitat

The change in habitat affects the gut microbial content. The salinity of water and temperature influence the microbial community. In black molly dominant microbes vary as the salinity increases, whereas in rainbow trout temperature changes the dominant microbes (Schmidt et al. 2015; Huyben et al. 2018). It has been observed that the microbial diversity varies between freshwater and marine habitat fishes (Vatsos 2016). Vibrio is the common microbes occurring in marine habitat fishes whereas in the freshwater fishes Aeromonas and Pseudomonas dominate (Vatsos 2016).

Various pollutants such as pesticides and heavy metals influence the gut microbial composition. In common carp and zebrafish, it has been observed that polystyrene microparticles and waterborne copper influence the microbes associated with the immunity (Meng et al. 2018; Jin et al. 2018).

In the captive state also, the gut microbes depend on many factors such as food ingredients, environment, and social behavior (Egerton et al. 2018). The altered gut microbiota in captive breeding has been reported in many freshwater and marine fish species (Bucio et al. 2006; Nelson et al. 2013). Under captive management, various factors such as stocking density, stress, feed, and use of antibiotics (Verschuere et al. 2000; Navarrete et al. 2008; Clements et al. 2014) can alter the gut microbiota. In the zebrafish model, it has been shown that there are changes in gut microbiota in captive and lab-reared fish; however, some microbes remained the same depending on their historical correlation (Roeselers et al. 2011). Various others also reported that although there are habitat-specific changes, there always exists some core microbiota (Roeselers et al. 2011).

5 Physiological Roles of Gut Microbiota

The gut microbial community modulates the host's physiology, and the host provides nutrients for the gut microbes (Rosenbaum et al. 2015). However, the gut microbial activity depends on the composition and the diversity of gut microbes (Vigneri 2014). The host physiology which can be affected by gut microbes is feeding, digestion, and metabolism; it also influences stress response, reproduction, growth, and immunity (Butt and Volkoff 2019).

5.1 Influence of Microbiota on Feeding and Metabolism

The gut microbes have a major role in the regulation of feeding, digestive process, and metabolism (Duca et al. 2012). In fishes, limited studies have been conducted to identify the effect of microbes on feeding and metabolism (Butt and Volkoff 2019). These microbes secrete short-chain fatty acid, indoles and butyrate, etc. in the form of metabolites and affect digestion and metabolism (Butt and Volkoff 2019). These microbiotas also influence the gut neurotransmitter such as serotonin, dopamine, etc., and affect the function of the gut such as motility, release of enzyme, and feeding behavior (Yano et al. 2015; Strandwitz 2018). The gut neurotransmitter also influences the microbes and modifies the discharge of cytokines (Mittal et al. 2017).

Some of the metabolites regulate the cells of the intestine and regulate their uptake, absorption, etc., and thus affect various metabolism such as adipogenesis (Bäckhed et al. 2004). The gut microbial release also modulates the secretion of gut enzymes and thus gut motility (Cani and Knauf 2016). The released microbial compounds may also circulate to reach the brain or may regulate the release of appetite-regulating peptides which may stimulate the release of central neuropeptides (Cussotto et al. 2018).

In fish also some studies have shown the influence of gut microbiota on metabolism. The microbial community can alter the metabolism pathway of carbohydrate, fat, and protein changes in grass carp (Ni et al. 2013). In zebrafish also it has been observed that change in gut microbes changes the lipid metabolism (Semova et al. 2012).

5.2 Effect of Gut Microbial Activity on Stress Response

Fishes may get stressed due to many factors such as poor water quality, lack of oxygen, temperature, and overcrowding. The stress affects the microbial community composition and changes the gut mucus and adversely affects the nutrient absorption and immunity of the host (Cantas et al. 2012). This may decrease the feeding rate and increase the chances of pathogen infection (Sekirov and Finlay 2009) as observed in goldfish and chinook salmon (Volkoff and Peter 2004; Bernier 2010). The microbes influence the hypothalamic-pituitary-adrenal (HPA) axis which is subjected to hormone control behavioral response such as feeding (Sudo 2014).

5.3 Effect of Gut Microbial Activity on Reproduction

The exact mechanism of gut microbes on reproduction is not clear. Some studies have shown that gut microbes help in gonadal development and reproduction (Butt and Volkoff 2019). In larval fish, the supplementation of probiotics improves their development and gonadal maturation as observed in zebrafish (Avella et al. 2012; Carnevali et al. 2013). In adult zebrafish and goldfish, the probiotic microbes improved gonadosomatic indexes (GSI), produced more eggs, higher reproductive gene expression, and higher reproductive success (Ghosh et al. 2007; Carnevali et al. 2013).

5.4 Effect of Gut Microbial Activity on Development

The gut microbes vary with the developmental stages. It has been found that as the fish grows their microbial diversity increases in grass carp (Wang et al. 2015). In Zebrafish the lack of microbes impaired the development of the gastrointestinal tract and the reversal of microbes may resume the function (Lescak and Milligan-Myhre 2017). The microbes may also influence neuronal development and affect the movement and feeding and ultimately the development of fish (Phelps et al. 2017).

5.5 Effect of Gut Microbial Activity on Immunity

The gut microbes play a critical role in developing the immune response of the host fish. The pathogens are defended by the intestinal microbes in host fishes (Kim et al. 2017). These pathogens could not interrupt the gut barrier and could not hamper the brain and intestine function (Ribet and Cossart 2015). The microbes present in the gut shows a competitive behavior for space with the pathogen, and they also secrete the antimicrobial peptides to disrupt the pathogen (Kim et al. 2017). In rainbow trout, it has been observed that supplementation of beneficial microbes enhances the immunity of the host (Adel et al. 2017).

6 Adaptive Strategy for Climatic Variability

The gut microbiota is allied with the health condition of fish. These microbes can be manipulated to enhance the health status of fish. Food and feeding alteration can change the gut microbial community. The inclusion of different proteins, lipids, probiotics, and prebiotics can alter the microbes of the gut and enhance health status (Egerton et al. 2018). The variation in diet and gut microbiota has been reported by various authors (Delcroix et al. 2015; Zarkasi et al. 2016), and it could be helpful as an adaptive strategy for climatic variations.

6.1 Protein

Protein acts as a source of energy in food. At the same time, the inclusion of different protein diets can also alter the gut microbiota. The type of protein and its quantity can affect the gut microbial structure (Desai et al. 2012; Geurden et al. 2014; Zarkasi et al. 2016). Peptides and glycopeptides produced after protein hydrolysis can make changes in the gut diversity (Swiatecka et al. 2012), and the supply of direct protein hydrolysates can act as a substrate for microbes and enhance their growth (Delcroix et al. 2015). The protein hydrolysate also helps to combat pathogenic bacteria, certain peptides act as antimicrobials whereas some amino acids regulate the immune pathway and synthesis of antibodies (Kiron 2012; Sila et al. 2014; Egerton et al. 2018). Thus they assist to improve the health status of fish.

6.2 Lipids

Lipid is also the main energy basis in fish. It has been found that increasing the lipid content enhances the gut microbial diversity (Lesel et al. 1989). Variation of lipid diet alters the microbial diversity in arctic char (Ringø et al. 2002). It has been shown that change of fish oil to plant-based oil improves the gut microbial community and immunity of fish against pathogens (Lødemel et al. 2001; Ringø et al. 2002). Various microbes isolated from the gut of fishes and invertebrates such as *Shewanella* sp. and *Vibrio* sp. produce polyunsaturated fatty acids (Monroig et al. 2013). These microbes can act as a potential probiotic (Egerton et al. 2018).

6.3 Probiotics

Probiotics are live microorganisms that supply health benefits to the host. These microorganisms are used as a substitute for antibiotics in aquaculture (Abelli et al. 2009). Among microorganisms, the gram-negative bacteria, gram-positive bacteria, bacteriophages, and yeasts could be used as probiotics (Akhter et al. 2015). Bacillus and Lactobacillus are the most recurrently used probiotics in aquaculture (Merrifield and Carnevali 2014). These microbes help to increase the growth rate and modulate the immune reaction of the host (Lobo et al. 2014; Cordero et al. 2015). In the aquaculture sector, these probiotics help to improve the health and nutritional status and reduce the cost (El-Haroun et al. 2006). However it is difficult to process, store, and feed the probiotics in aquaculture (Merrifield et al. 2010).

6.4 Prebiotic

Prebiotics are the substrates used to confer a health benefit in host fishes in a selective mode (Cremon et al. 2018). The commonly used prebiotics are fructooligosaccharides, mannan-oligosaccharides, inulin, and *trans*-galactooligosaccharides (Ringø et al. 2016). The prebiotic also helps to improve the growth, feed conversion, nutrient uptake, and immunity of fish (Bongers and van den Heuvel 2003; Torrecillas et al. 2007; Adel et al. 2016). However, the success of prebiotic administration depends on the age of the fish, species of fish culture condition, and dose of prebiotics (Torrecillas et al. 2014).

7 Next-Generation Sequencing Study of Gut Microbes

A detailed understanding between intestinal microbiota and their host fish can depict the function and dysfunction of the host organism. Conventional culture-dependent studies on fish intestinal microbiota were conducted over the last decades (Cahill 1990). However, these microbiotas only indicate $<0.1\%$ of the total microbial community in the intestine of host fishes with low cultivability (Romero and Navarrete 2006; Navarrete et al. 2009; Zhou et al. 2014; Ghanbari et al. 2015). With the advancement in DNA sequencing and bioinformatics, extensive molecular ecology-based methods on the 16S and 23S rRNA genes have become more frequently used recently.

The next-generation sequencing (NGS) technology based on the 16S and 23S rRNA and the development of various bioinformatics software has advanced the knowledge of these microbial taxa. More efficient and budget-friendly approaches to NGS technologies have gained wide attention for studying the high dense gut microbiota composition and its genetic potential (Ghanbari et al. 2015). The emerging rapid and reliable NGS techniques can enrich the knowledge of the fish gut microbial community with promising results.

8 Conclusion

Fish gut microbes affect the physiology, immunity, and growth of fish. The gut microbial composition of fish varies in different fish species and within fish species differs in different life stages. The various intrinsic and extrinsic factors also influence the gut microbes and their activity. Fish gut microbial composition differed depending on species, sex, habitat, and feeding behavior. The gut microbial manipulation through prebiotics has the potential to promote the growth and health condition of fish.

References

Abelli L, Randelli E, Carnevali O, Picchietti S (2009) Stimulation of gut immune system by early administration of probiotic strains in *Dicentrarchus labrax* and *Sparus aurata*. Ann N Y Acad Sci 1163:340–342. https://doi.org/10.1111/j.1749-6632.2008.03670.x

Adel M, Nayak S, Lazado CC, Yeganeh S (2016) Effects of dietary prebiotic GroBiotic®—a on growth performance, plasma thyroid hormones and mucosal immunity of great sturgeon, Husohuso (Linnaeus, 1758). J Appl Ichthyol 32:825–831. https://doi.org/10.1111/jai.13153

Adel M, Lazado CC, Safari R, Yeganeh S, Zorriehzahra MJ (2017) AqualaseR, a yeast-based in-feed probiotic, modulates intestinal microbiota, immunity and growth of rainbow trout Oncorhynchus mykiss. Aquac Res 48:1815–1826. https://doi.org/10.1111/are.13019

Akhter N, Wu B, Memon AM, Mohsin M (2015) Probiotics and prebiotics associated with aquaculture: a review. Fish Shellfish Immunol 45:733–741. https://doi.org/10.1016/j.fsi.2015.05.038

Al-Harbi AH, Uddin MN (2004) Seasonal variation in the intestinal bacterial flora of hybrid tilapia (Oreochromis niloticus × Oreochromis aureus) cultured in earthen ponds in Saudi Arabia. Aquaculture 229:37–44. https://doi.org/10.1016/S0044-8486(03)00388-0

Apajalahti J (2005) Comparative gut microflora, metabolic challenges, and potential opportunities. J Appl Poult Res 14(2):444–453

Aschfalk A, Muller W (2002) Clostridium perfringens toxin types from wild-caught Atlantic cod (Gadus morhua L.), determined by PCR and ELISA. Can J Microbiol 48:365–368

Avella MA, Place A, Du SJ, Williams E, Silvi S, Zohar Y et al (2012) Lactobacillus rhamnosus accelerates zebrafish backbone calcification and gonadal differentiation through effects on the GnRH and IGF systems. PLoS One 7:e45572. https://doi.org/10.1371/journal.pone.004557258

Bäckhed F, Ding H, Wang T, Hooper LV, Koh GY, Nagy A et al (2004) The gut microbiota as an environmental factor that regulates fat storage. Proc Natl Acad Sci U S A 101:15718–15723. https://doi.org/10.1073/pnas.0407076101

Bano N, deRae Smith A, Bennett W, Vasquez L, Hollibaugh JT (2007) Dominance of Mycoplasma in the guts of the long-jawed mudsucker, Gillichthys mirabilis, from five California salt marshes. Environ Microbiol 9:2636–2641

Bates JM, Mittge E, Kuhlman J, Baden KN, Cheesman SE, Guillemin K (2006) Distinct signals from the microbiota promote different aspects of zebrafish gut differentiation. Dev Biol 297:374–386

Bernier NJ (2010) Food intake regulation and disorders. Fish Dis Disord 2:238–266. https://doi.org/10.1079/9781845935535.0238

Bletz MC, Archer H, Harris RN, McKenzie VJ, Rabemananjara FC, Rakotoarison A, Vences M (2017) Host ecology rather than host phylogeny drives amphibian skin microbial community structure in the biodiversity hotspot of Madagascar. Front Microbiol 8:1530

Bolnick DI, Snowberg LK, Hirsch PE, Lauber CL, Org E, Parks B et al (2014) Individual diet has sex-dependent effects on vertebrate gut microbiota. Nat Commun 5:ncomms5500. https://doi.org/10.1038/ncomms5500

Bongers A, van den Heuvel EG (2003) Prebiotics and the bioavailability of minerals and trace elements. Food Rev Int 19:397–422. https://doi.org/10.1081/FRI120025482

Brugman S, Ikeda-Ohtsubo W, Braber S, Folkerts G, Pieterse CM, Bakker PA (2018) A comparative review on microbiota manipulation: lessons from fish, plants, livestock, and human research. Front Nutr 5:80

Bucio A, Hartemink R, Schrama JW, Verreth J, Rombouts FM (2006) Presence of lactobacilli in the intestinal content of freshwater fish from a river and from a farm with a recirculation system. Food Microbiol 23:476–482. https://doi.org/10.1016/j.fm.2005.06.001

Butt RL, Volkoff H (2019) Gut microbiota and energy homeostasis in fish. Front Endocrinol 10:9

Cahill MM (1990) Bacterial flora of fishes: a review. Microb Ecol 19:21–41. https://doi.org/10.1007/BF02015051

Campbell AC, Buswell JA (1983) The intestinal microflora of farmed Dover sole (Solea solea) at different stages of fish development. J Appl Microbiol 55:215–223. https://doi.org/10.1111/j.1365-2672.1983.tb01318.x

Cani PD, Knauf C (2016) How gut microbes talk to organs: the role of endocrine and nervous routes. Mol Metabol 5:743–752. https://doi.org/10.1016/j.molmet.2016.05.011

Cantas L, Sorby JR, Alestrom P, Sorum H (2012) Culturable gut microbiota diversity in zebrafish. Zebrafish 9:26–37. https://doi.org/10.1089/zeb.2011.0712

Carlson JM, Leonard AB, Hyde ER, Petrosino JF, Primm TP (2017) Microbiome disruption and recovery in the fish Gambusia affinis following exposure to broad-spectrum antibiotic. Infect Drug Resist 10:143

Carnevali O, Avella MA, Gioacchini G (2013) Effects of probiotic administration on zebrafish development and reproduction. Gen Comp Endocrinol 188:297–302. https://doi.org/10.1016/j.ygcen.2013.02.022

Clements KD, Pasch IB, Moran D, Turner SJ (2007) Clostridia dominate 16S rRNA gene libraries prepared from the hindgut of temperate marine herbivorous fishes. Mar Biol 150:1431–1440. https://doi.org/10.1007/s00227-006-0443-9

Clements KD, Angert ER, Montgomery WL, Choat JH (2014) Intestinal microbiota in fishes: what's known and what's not. Mol Ecol 23:1891–1898. https://doi.org/10.1111/mec.12699

Cordero H, Guardiola FA, Tapia-Paniagua ST, Cuesta A, Meseguer J, Balebona MC et al (2015) Modulation of immunity and gut microbiota after dietary administration of alginate encapsulated Shewanella putrefaciens Pdp11 to gilthead seabream (Sparus aurata L.). Fish Shellfish Immunol 45:608–618. https://doi.org/10.1016/j.fsi.2015.05.010

Cremon C, Barbaro MR, Ventura M, Barbara G (2018) Pre-and probiotic overview. Curr Opin Pharmacol 43:87–92

Curson AR, Sullivan MJ, Todd JD, Johnston AW (2010) Identification of genes for dimethyl sulfide production in bacteria in the gut of Atlantic Hrring (Clupea harengus). ISME J 4:144–146. https://doi.org/10.1038/ismej.2009.93

Cussotto S, Sandhu KV, Dinan TG, Cryan JF (2018) The neuroendocrinology of the microbiota-gut-brain axis: a behavioural perspective. Front Neuroendocrinol 51:80–101. https://doi.org/10.1016/j.yfrne.2018.04.002

Delcroix J, Gatesoupe FJ, Desbruyères E, Huelvan C, Le Delliou H, Le Gall MM, Quazuguel P et al (2015) The effects of dietary marine protein hydrolysates on the development of sea bass larvae, Dicentrarchus labrax, and associated microbiota. Aquac Nutr 21:98–104. https://doi.org/10.1111/anu.12139

Desai AR, Links MG, Collins SA, Mansfield GS, Drew MD, Van Kessel AG et al (2012) Effects of plant-based diets on the distal gut microbiome of rainbow trout (Oncorhynchus mykiss). Aquaculture 350:134–142. https://doi.org/10.1016/j.aquaculture.2012.04.005

Dhanasiri AK, Brunvold L, Brinchmann MF, Korsnes K, Bergh O, Kiron V (2011) Changes in the intestinal microbiota of wild Atlantic cod Gadus morhua L. upon captive rearing. Microb Ecol 61:20–30. https://doi.org/10.1007/s00248-010-9673-y

Di Maiuta N, Schwarzentruber P, Schenker M, Schoelkopf J (2013) Microbial population dynamics in the faeces of woodeating loricariid catfishes. Lett Appl Microbiol 56:401–407

Duca FA, Swartz TD, Sakar Y, Covasa M (2012) Increased oral detection, but decreased intestinal signaling for fats in mice lacking gut microbiota. PLoS One 7:e39748. https://doi.org/10.1371/journal.pone.0039748

Egerton S, Culloty S, Whooley J, Stanton C, Ross RP (2018) The gut microbiota of marine fish. Front Microbiol 9:873. https://doi.org/10.3389/fmicb.2018.00873

Eichmiller JJ, Hamilton MJ, Staley C, Sadowsky MJ, Sorensen PW (2016) Environment shapes the fecal microbiome of invasive carp species. Microbiome 4:44. https://doi.org/10.1186/s40168-016-0190-1

El-Haroun E, Goda AS, Chowdhury K (2006) Effect of dietary probiotic Biogen R supplementation as a growth promoter on growth performance and feed utilization of Nile tilapia Oreochromis niloticus (L.). Aquac Res 37:1473–1480. https://doi.org/10.1111/j.1365-2109.2006.01584.x

Fernandez RD, Tendencia EA, Leano EM, Duray MN (1996) Bacterial flora of milkfish, Chanos chanos, eggs and larvae. Fish Pathol 31:123–128. https://doi.org/10.3147/jsfp.31.123

Fidopiastis PM, Bezdek DJ, Horn MH, Kandel JS (2006) Characterizing the resident, fermentative microbial consortium in the hindgut of the temperate-zone herbivorous fish, Hermosilla azurea (Teleostei: Kyphosidae). Mar Biol 148:631–642

Floris R, Manca S, Fois N (2013) Microbial ecology of intestinal tract of gilthead sea bream (Sparus aurata Linnaeus, 1758) from two coastal lagoons of Sardinia (Italy). Trans Waters Bull 7:4–12

Gajardo K, Jaramillo-Torres A, Kortner TM, Merrifield DL, Tinsley J, Bakke AM, Krogdahl Å (2017) Alternative protein sources in the diet modulate microbiota and functionality in the distal intestine of Atlantic salmon (Salmo salar). Appl Environ Microbiol 83(5):e02615–e02616

Gatesoupe F-J, Infante JLZ, Cahu C, Quazuguel P (1997) Early weaning of seabass larvae, Dicentrarchus labrax: the effect on microbiota, with particular attention to iron supply and exoenzymes. Aquaculture 158:117–127. https://doi.org/10.1016/S0044-8486(97)00179-8

Gatesoupe FJ, Huelvan C, Le Bayon N, Le Delliou H, Madec L, Mouchel O, Quazuguel P, Mazurais D, Zambonino-Infante JL (2016) The highly variable microbiota associated to intestinal mucosa correlates with growth and hypoxia resistance of sea bass, Dicentrarchus labrax, submitted to different nutritional histories. BMC Microbiol 16(1):1–13

Geraylou Z, Souffreau C, Rurangwa E, Maes GE, Spanier KI, Courtin CM et al (2013) Prebiotic effects of arabinoxylan oligosaccharides on juvenile Siberian sturgeon (Acipenser baerii) with emphasis on the modulation of the gut microbiota using 454 pyrosequencing. FEMS Microbiol Ecol 86:357–371

Geurden I, Mennigen J, Plagnes-Juan E, Veron V, Cerezo T, Mazurais D et al (2014) High or low dietary carbohydrate: protein ratios during first-feeding affect glucose metabolism and intestinal microbiota in juvenile rainbow trout. J Exp Biol 217:3396–3406. https://doi.org/10.1242/jeb.106062

Ghanbari M, Kneifel W, Domig KJ (2015) A new view of the fish gut microbiome: advances from next-generation sequencing. Aquaculture 448:464–475. https://doi.org/10.1016/j.aquaculture.2015.06.033

Ghosh S, Sinha A, Sahu C (2007) Effect of probiotic on reproductive performance in female livebearing ornamental fish. Aquac Res 38:518–526. https://doi.org/10.1111/j.1365-2109.2007.01696.x

Givens CE, Ransom B, Bano N, Hollibaugh JT (2015) Comparison of the gut microbiomes of 12 bony fish and 3 shark species. Mar Ecol Prog Ser 518:209–223

Green TJ, Smullen R, Barnes AC (2013) Dietary soybean protein concentrate-induced intestinal disorder in marine farmed Atlantic salmon, Salmo salar is associated with alterations in gut microbiota. Vet Microbiol 166:286–292

Gueimonde M, Sakata S, Kalliomäki M, Isolauri E, Benno Y, Salminen S (2006) Effect of maternal consumption of lactobacillus GG on transfer and establishment of fecal bifidobacterial microbiota in neonates. J Pediatr Gastroenterol Nutr 42(2):166–170

Hagi T, Tanaka D, Iwamura Y, Hoshino T (2004) Diversity and seasonal changes in lactic acid bacteria in the intestinal tract of cultured freshwater fish. Aquaculture 234:335–346. https://doi.org/10.1016/j.aquaculture.2004.01.018

Han S, Liu Y, Zhou Z, He S, Cao Y, Shi P et al (2010) Analysis of bacterial diversity in the intestine of grass carp (Ctenopharyngodon idellus) based on 16S rDNA gene sequences. Aquac Res 42: 47–56

Hansen G, Olafsen J (1999) Bacterial interactions in early life stages of marine cold water fish. Microb Ecol 38:1–26. https://doi.org/10.1007/s002489900158

Hansen G, Strøm E, Olafsen J (1992) Effect of different holding regimens on the intestinal microflora of herring (Clupea harengus) larvae. Appl Environ Microbiol 58:461–470

Holben W, Williams P, Saarinen M, Särkilahti L, Apajalahti J (2002) Phylogenetic analysis of intestinal microflora indicates a novel Mycoplasma phylotype in farmed and wild salmon. Microb Ecol 44:175–185

Hovda MB, Fontanillas R, McGurk C, Obach A, Rosnes JT (2012) Seasonal variations in the intestinal microbiota of farmed Atlantic salmon (Salmo salar L.). Aquac Res 43:154–159. https://doi.org/10.1111/j.1365-2109.2011.02805.x

Huyben D, Sun L, Moccia R, Kiessling A, Dicksved J, Lundh T (2018) Dietary live yeast and increased water temperature influence the gut microbiota of rainbow trout. J Appl Microbiol 124:1377–1392. https://doi.org/10.1111/jam.13738

Itoi S, Okamura T, Koyama Y, Sugita H (2006) Chitinolytic bacteria in the intestinal tract of Japanese coastal fishes. Can J Microbiol 52:1158–1163. https://doi.org/10.1139/w06-082

Jin Y, Xia J, Pan Z, Yang J, Wang W, Fu Z (2018) Polystyrene microplastics induce microbiota dysbiosis and inflammation in the gut of adult zebrafish. Environ Pollut 235:322–329. https://doi.org/10.1016/j.envpol.2017.12.088

Karthiayani T, Mahadeva Iyer K (1967) Quantitative and qualitative studies on the bacterial flora of fresh sardines. Fish Technol 4:89–97

Kim S, Covington A, Pamer EG (2017) The intestinal microbiota: antibiotics, colonization resistance, and enteric pathogens. Immunol Rev 279:90–105. https://doi.org/10.1111/imr.12563

Kiron V (2012) Fish immune system and its nutritional modulation for preventive health care. Anim Feed Sci Technol 173:111–133. https://doi.org/10.1016/j.anifeedsci.2011.12.015

Koo H, Hakim JA, Powell ML, Kumar R, Eipers PG, Morrow CD, Crowley M, Lefkowitz EJ, Watts SA, Bej AK (2017) Metagenomics approach to the study of the gut microbiome structure and function in zebrafish Danio rerio fed with gluten formulated diet. J Microbiol Methods 135: 69–76

Larsen AM (2014) Studies on the microbiota of fishes and the factors influencing their composition. Auburn University, Auburn

Lauzon HL, Gudmundsdottir S, Petursdottir SK, Reynisson E, Steinarsson A, Oddgeirsson M et al (2010) Microbiota of Atlantic cod (Gadus morhua L.) rearing systems at pre- and posthatch stages and the effect of different treatments. J Appl Microbiol 109(5):1775–1789

Lescak EA, Milligan-Myhre KC (2017) Teleosts as model organisms to understand host-microbe interactions. J Bacteriol 199:e00868-16. https://doi.org/10.1128/JB.00868-16

Lesel R, De La Noüe J, Choubert G (1989) Fecal bacterial flora of rainbow trout under antibiotic treatment: effect of the number of pyloric caeca and the lipid content of food. In: De Pauw N, Jaspers E, Ackefors H, Wilkins N (eds) Aquaculture: a biotechnology in progress, vol 1. European Aquaculture Society, Bredene, p 592

Li T et al (2017) Bacterial signatures of "red-operculum" disease in the gut of crucian carp (Carassius auratus). Microbial Ecol 74:510–521. https://doi.org/10.1007/s00248-017-0967-1

Li X, Yu Y, Li C, Yan Q (2018) Comparative study on the gut microbiotas of four economically important Asian carp species. Sci China Life Sci 11:1–10. https://doi.org/10.1007/s11427-016-9296-5

Liu Y, Yao Y, Li H, Qiao F, Wu J, Du ZY et al (2016) Influence of endogenous and exogenous estrogenic endocrine on intestinal microbiota in zebrafish. PLoS One 11:e0163895. https://doi.org/10.1371/journal.pone.0163895

Lobo C, Moreno-Ventas X, Tapia-Paniagua S, Rodríguez C, Moriñigo MA, de La Banda IG (2014) Dietary probiotic supplementation (Shewanella putrefaciens Pdp11) modulates gut microbiota and promotes growth and condition in Senegalese sole larviculture. Fish Physiol Biochem 40: 295–309. https://doi.org/10.1007/s10695-013-9844-0

Lødemel JB, Mayhew TM, Myklebust R, Olsen RE, Espelid S, Ringø E (2001) Effect of three dietary oils on disease susceptibility in Arctic charr (Salvelinus alpinus L.) during cohabitant challenge with Aeromonas salmonicida ssp. salmonicida. Aquac Res 32:935–945. https://doi.org/10.1046/j.1365-2109.2001.00621.x

Lokesh J, Kiron V, Sipkema D, Fernandes JMO, Moum T (2018) Succession of embryonic and the intestinal bacterial communities of Atlantic salmon (Salmo salar) reveals stage-specific microbial signatures. Microbiol Open 13:e00672. https://doi.org/10.1002/mbo3.672

Lyons PP, Turnbull JF, Dawson KA, Crumlish M (2017) Phylogenetic and functional characterization of the distal intestinal microbiome of rainbow trout Oncorhynchus mykiss from both farm and aquarium settings. J Appl Microbiol 122:347–363. https://doi.org/10.1111/jam.13347

MacDonald N, Stark J, Austin B (1986) Bacterial microflora in the gastrointestinal tract of Dover sole (Solea solea L.), with emphasis on the possible role of bacteria in the nutrition of the host. FEMS Microbiol Lett 35:107–111. https://doi.org/10.1111/j.1574-6968.1986.tb01508.x

MacFarlane RD, McLaughlin JJ, Bullock G (1986) Quantitative and qualitative studies of gut flora in striped bass from estuarine and coastal marine environments. J Wildl Dis 22:344–348

Macmillan JR, Santucci T (1990) Seasonal trends in intestinal bacterial flora of farm-raised channel catfish. J Aquat Anim Health 2:217–222. https://doi.org/10.1577/1548-8667(1990)0022.3.CO;2

Martin-Antonio B, Manchado M, Infante C, Zerolo R, Labella A, Alonso C et al (2007) Intestinal microbiota variation in Senegalese sole (Solea senegalensis) under different feeding regimes. Aquac Res 38:1213–1222

Meng XL, Li S, Qin CB, Zhu ZX, Hu WP, Yang LP et al (2018) Intestinal microbiota and lipid metabolism responses in the common carp (Cyprinus carpio L.) following copper exposure. Ecotoxicol Environ Saf 160:257–264. https://doi.org/10.1016/j.ecoenv.2018.05.050

Merrifield DL, Carnevali O (2014) Probiotic modulation of the gut microbiota of fish. In: Merrifield D, Ringø E (eds) Aquaculture nutrition: gut health, probiotics and prebiotics. John Wiley & Sons, Ltd., Chichester, pp 185–222

Merrifield DL, Dimitroglou A, Foey A, Davies SJ, Baker RT, Bøgwald J et al (2010) The current status and future focus of probiotic and prebiotic applications for salmonids. Aquaculture 302: 1–18. https://doi.org/10.1016/j.aquaculture.2010.02.007

Michl SC, Ratten JM, Beyer M, Hasler M, LaRoche J, Schulz C (2017) The malleable gut microbiome of juvenile rainbow trout (Oncorhynchus mykiss): diet-dependent shifts of bacterial community structures. PLoS One 12(5):e0177735

Mittal R, Debs LH, Patel AP, Nguyen D, Patel K, O'Connor G et al (2017) Neurotransmitters: the critical modulators regulating gut-brain axis. J Cell 232:2359

Miyake S, Ngugi DK, Stingl U (2015) Diet strongly influences the gut microbiota of surgeonfishes. Mol Ecol 24:656–672. https://doi.org/10.1111/mec.13050

Monroig Ó, Tocher DR, Navarro JC (2013) Biosynthesis of polyunsaturated fatty acids in marine invertebrates: recent advances in molecular mechanisms. Mar Drugs 11:3998–4018. https://doi.org/10.3390/md11103998

Moran D, Turner S, Clements K (2005) Ontogenetic development of the gastrointestinal microbiota in the marine herbivorous fish Kyphosus sydneyanus. Microb Ecol 49:590–597

Mouchet MA, Bouvier C, Bouvier T, Troussellier M, Escalas A, Mouillot D (2012) Genetic difference but functional similarity among fish gut bacterial communities through molecular and biochemical fingerprints. FEMS Microbiol Ecol 79:568–580. https://doi.org/10.1111/j.1574-6941.2011.01241.x

Munro PD, Barbour A, Birkbeck TH (1994) Comparison of the gut bacterial flora of start-feeding larval turbot reared under different conditions. J Appl Microbiol 77:560–566. https://doi.org/10.1111/j.1365-2672.1994.tb04402.x

Muroga K, Higashia M, Keitoku H (1987) The isolation of intestinal microflora of farmed red seabream (Pagrus major) and black seabream (Acanthopagrus schlegeli) at larval and juvenile stages. Aquaculture 65:79–88. https://doi.org/10.1016/0044-8486(87)90272-9

Navarrete P, Mardones P, Opazo R, Espejo R, Romero J (2008) Oxytetracycline treatment reduces bacterial diversity of intestinal microbiota of Atlantic salmon. J Aquat Anim Health 20:177–183. https://doi.org/10.1577/H07-043.1

Navarrete P, Espejo RT, Romero J (2009) Molecular analysis of microbiota along the digestive tract of juvenile Atlantic salmon (Salmo salar L.). Microb Ecol 57:550–561. https://doi.org/10.1007/s00248-008-9448-x

Navarrete P, Magne F, Araneda C, Fuentes P, Barros L, Opazo R et al (2012) PCR-TTGE analysis of 16S rRNA from rainbow trout (Oncorhynchus mykiss) gut microbiota reveals host-specific communities of active bacteria. PLoS One 7:e31335

Nelson TM, Rogers TL, Carlini AR, Brown MV (2013) Diet and phylogeny shape the gut microbiota of Antarctic seals: a comparison of wild and captive animals. Environ Microbiol 15:1132–1145. https://doi.org/10.1111/1462-2920.12022

Neuman C, Hatje E, Zarkasi KZ, Smullen R, Bowman JP, Katouli M (2016) The effect of diet and environmental temperature on the faecal microbiota of farmed Tasmanian Atlantic Salmon (Salmo salar L.). Aquac Res 47:660–672. https://doi.org/10.1111/are.12522

Newman JTJ, Cosenza BJ, Buck JD (1972) Aerobic microflora of the bluefish (Pomatomus saltatrix) intestine. J Fish Res Board Can 29:333–336

Ni J, YanQ YY, Zhang T (2013) Factors influencing the grass carp gut microbiome and its effect on metabolism. FEMS Microbiol Ecol 87:704–714. https://doi.org/10.1111/1574-6941.12256

Nie L, Zhou QJ, Qiao Y, Chen J (2017) Interplay between the gut microbiota and immune responses of ayu (Plecoglossus altivelis) during Vibrio anguillarum infection. Fish Shellfish Immunol 68: 479–487

Nielsen S, Walburn JW, Verges A, Thomas T, Egan S (2017) Microbiome patterns across the gastrointestinal tract of the rabbitfish Siganus fuscescens. PeerJ 5:e3317

Ornelas-García P, Pajares S, Sosa-Jiménez VM, Rétaux S, Miranda-Gamboa RA (2018) Microbiome differences between river-dwelling and cave-adapted populations of the fish Astyanax mexicanus (De Filippi, 1853). PeerJ 6:e5906

Parris DJ, Brooker RM, Morgan MA, Dixson DL, Stewart FJ (2016) Whole gut microbiome composition of damselfish and cardinalfish before and after reef settlement. PeerJ 4:e2412

Phelps D, Brinkman NE, Keely SP, Anneken EM, Catron TR, Betancourt D et al (2017) Microbial colonization is required for normal neurobehavioral development in zebrafish. Sci Rep 7:11244. https://doi.org/10.1038/s41598-017-10517-5

Prasanth B, Venkatesh K, Rajesh P, Gayathri R, Kanchana M, Nurul Amin SM et al (2018) A mini review on immune role of chemokines and its receptors in snakehead murrel Channa striatus. Fish Shellfish Immunol 72:670–678

Prince AL, Antony KM, Chu DM, Aagaard KM (2014) The microbiome, parturition, and timing of birth: more questions than answers. J Reprod Immunol 104–105:12–19. https://doi.org/10.1016/j.jri.2014.03.006

Ransom BL (2008) Intestinal microbial community composition of six Actinopterygii fish species in the southeastern United States. University of Georgia, Athens

Reid HI, Treasurer JW, Adam B, Birkbeck TH (2009) Analysis of bacterial populations in the gut of developing cod larvae and identification of Vibrio logei, Vibrio anguillarum and Vibrio splendidus as pathogens of cod larvae. Aquaculture 288:36–43

Ribet D, Cossart P (2015) How bacterial pathogens colonize their hosts and invade deeper tissues. Microbes Infect 17:173–183. https://doi.org/10.1016/j.micinf.2015.01.004

Ringø E, Birkbeck TH (1999) Intestinal microflora of fish larvae and fry. Aquac Res 30:73–93. https://doi.org/10.1046/j.1365-2109.1999.00302.x

Ringø E, Lødemel JB, Myklebust R, Jensen L, Lund V, Mayhew TM et al (2002) The effects of soybean, linseed and marine oils on aerobic gut microbiota of Arctic charr Salvelinus alpinus L. before and after challenge with Aeromonas salmonicida ssp. salmonicida. Aquac Res 33: 591–606. https://doi.org/10.1046/j.1365-2109.2002.00697.x

Ringø E, Zhou Z, Vecino JLG, Wadsworth S, Romero J, Krogdahl Å et al (2016) Effect of dietary components on the gut microbiota of aquatic animals. A never-ending story? Aquac Nutr 22: 219–282. https://doi.org/10.1111/anu.12346

Roeselers G, Mittge EK, Stephens WZ, Parichy DM, Cavanaugh CM, Guillemin K et al (2011) Evidence for a core gut microbiota in the zebrafish. ISME J 5:1595–1608. https://doi.org/10.1038/ismej.2011.38

Romero J, Navarrete P (2006) 16S rDNA-based analysis of dominant bacterial populations associated with early life stages of coho salmon (Oncorhynchus kisutch). Microb Ecol 51: 422–430. https://doi.org/10.1007/s00248-006-9037-9

Rosenbaum M, Knight R, Leibel RL (2015) The gut microbiota in human energy homeostasis and obesity. Trends Endocrinol Metab 26:493–501. https://doi.org/10.1016/j.tem.2015.07.002

Russo P, Iturria I, Mohedano ML, Caggianiello G, Rainieri S, Fiocco D, Angel Pardo M, López P, Spano G (2015) Zebrafish gut colonization by mCherry-labelled lactic acid bacteria. Appl Microbiol Biotechnol 99(8):3479–3490

Schmidt VT, Smith KF, Melvin DW, Amaral-Zettler LA (2015) Community assembly of a euryhaline fish microbiome during salinity acclimation. Mol Ecol 24:2537–2550. https://doi.org/10.1111/mec.13177

Sekirov I, Finlay BB (2009) The role of the intestinal microbiota in enteric infection. J Physiol 587: 4159–4167. https://doi.org/10.1113/jphysiol.2009.172742

Semova I, Carten JD, Stombaugh J, Mackey LC, Knight R, Farber SA et al (2012) Microbiota regulate intestinal absorption and metabolism of fatty acids in the zebrafish. Cell Host Microbe 12:277–288. https://doi.org/10.1016/j.chom.2012.08.003

Sila A, Nedjar-Arroume N, Hedhili K, Chataigné G, Balti R, Nasri M et al (2014) Antibacterial peptides from barbel muscle protein hydrolysates: activity against some pathogenic bacteria. LWT Food Sci Technol 55:183–188. https://doi.org/10.1016/j.lwt.2013.07.021

Skrodenyte-Arbaciauskiene V, Sruoga A, Butkauskas D (2006) Assessment of microbial diversity in the river trout Salmotrutta fario L. intestinal tract identified by partial 16S rRNA gene sequence analysis. Fish Sci 72:597–602

Skrodenyte-Arbačiauskiene V, Sruoga A, Butkauskas D, Skrupskelis K (2008) Phylogenetic analysis of intestinal bacteria of freshwater salmon Salmo salar and sea trout Salmo trutta trutta and diet. Fish Sci 74:1307–1314. https://doi.org/10.1111/j.1444-2906.2008.01656.x

Smriga S, Sandin SA, Azam F (2010) Abundance, diversity, and activity of microbial assemblages associated with coral reef fish guts and feces. FEMS Microbiol Ecol 73:31–42

Star B, Haverkamp TH, Jentoft S, Jakobsen KS (2013) Next generation sequencing shows high variation of the intestinal microbial species composition in Atlantic cod caught at a single location. BMC Microbiol 13:248

Strandwitz P (2018) Neurotransmitter modulation by the gut microbiota. Brain Res 1693:128–133. https://doi.org/10.1016/j.brainres.2018.03.015

Strøm E, Ringø E (1993) Changes in bacterial flora in developing cod, Gadus morhua (L.), larvae after inoculation of lactobacillus plantarum in the water. In: Walther B, Fyhn HJ (eds) Physiological and biochemical aspects of fish larval development. University of Bergen, Bergen, pp 226–228

Sudo N (2014) Microbiome, HPA axis and production of endocrine hormones in the gut. In: Microbial endocrinology: the microbiota-gut-brain axis in health and disease. Springer, New York, pp 177–194

Sugita H, Iwata J, Miyajima C, Kubo T, Noguchi T, Hashimoto K et al (1989) Changes in microflora of a puffer fish Fugu niphobles, with different water temperatures. Mar Biol 101: 299–304

Sullam KE, Essinger SD, Lozupone CA, O'Connor MP, Rosen GL, Knight R et al (2012) Environmental and ecological factors that shape the gut bacterial communities of fish: a meta-analysis. Mol Ecol 21:3363–3378. https://doi.org/10.1111/j.1365-294X.2012.05552.x

Sun Y, Yang H, Ling Z, Chang J, Ye J (2009) Gut microbiota of fast and slow growing grouper Epinephelus coioides. Afr J Microbiol Res 3:637–640

Svanevik CS, Lunestad BT (2011) Characterisation of the microbiota of Atlantic mackerel (Scomber scombrus). Int J Food Microbiol 151:164–170

Swiatecka D, Markiewicz LH, Wróblewska B (2012) Experimental immunology pea protein hydrolysate as a factor modulating the adhesion of bacteria to enterocytes, epithelial proliferation and cytokine secretion—an in vitro study. Cent Eur J Immunol 37:227–231. https://doi.org/10.5114/ceji.2012.30798

Tanasomwang V, Muroga K (1989) Intestinal microflora of rockfish Sebastes schlegeli, tiger puffer Takifugu rubripes and red grouper Epinephelus akaara at their larval and juvenile stages. Nippon Suisan Gakkaishi 55:1371–1377

Torrecillas S, Makol A, Caballero M, Montero D, Robaina L, Real F et al (2007) Immune stimulation and improved infection resistance in European sea bass (Dicentrarchus labrax) fed mannan oligosaccharides. Fish Shellfish Immunol 23:969–981. https://doi.org/10.1016/j.fsi.2007.03.007

Torrecillas S, Montero D, Izquierdo M (2014) Improved health and growth of fish fed mannan oligosaccharides: potential mode of action. Fish Shellfish Immunol 36:525–544. https://doi.org/10.1016/j.fsi.2013.12.029

Uchii K, Matsui K, Yonekura R, Tani K, Kenzaka T, Nasu M, Kawabata ZI (2006) Genetic and physiological characterization of the intestinal bacterial microbiota of bluegill (Lepomis macrochirus) with three different feeding habits. Microb Ecol 51(3):277–284

Vatsos IN (2016) Standardizing the microbiota of fish used in research. Lab Anim 51:353–364. https://doi.org/10.1177/0023677216678825

Verner-Jeffreys DW, Shields RJ, Bricknell IR, Birkbeck TH (2003) Changes in the gut-associated microflora during the development of Atlantic halibut (Hippoglossus hippoglossus L.) larvae in three British hatcheries. Aquaculture 219:21–42

Verschuere L, Rombaut G, Sorgeloos P, Verstraete W (2000) Probiotic bacteria as biological control agents in aquaculture. Microbiol Mol Biol Rev 64:655–671. https://doi.org/10.1128/MMBR.64.4.655-671.2000

Vigneri S (2014) The brain-gut axis: from pathophysiology to possible future strategies of treatment. Brain Disord Ther 3:137. https://doi.org/10.4172/2168-975X.1000137

Volkoff H, Peter RE (2004) Effects of lipopolysaccharide treatment on feeding of goldfish: role of appetite-regulating peptides. Brain Res 998:139–147

Wang W, Wu S, Zheng Y, Cheng Y, Li W, Zou H et al (2015) Characterization of the bacterial community associated with early-developmental stages of grass carp (Ctenopharyngodon idella). Aquac Res 46:2728–2735. https://doi.org/10.1111/are.12428

Wang AR, Ran C, Ringø E, Zhou ZG (2018) Progress in fish gastrointestinal microbiota research. Rev Aquacult 10:626–640. https://doi.org/10.1111/raq.12191

Ward NL, Steven B, Penn K, Methe BA, Detrich WH (2009) Characterization of the intestinal microbiota of two Antarctic notothenioid fish species. Extremophiles 13:679–685

Whipps J, Lewis K, Cooke R (1988) Mycoparasitism and plant disease control. In: Burge M (ed) Fungi in biological control systems. Manchester University Press, Manchester, pp 161–187. ISBN 9780719019791

Yan Q, Li J, Yu Y, Wang J, He Z, Van Nostrand JD, Kempher ML, Wu L, Wang Y, Liao L, Li X, Wu S, Ni J, Wang C, Zhou J (2016) Environmental filtering decreases with fish development for the assembly of gut microbiota. Environ Microbiol 18(12):4739–4754

Yano JM, Yu K, Donaldson GP, Shastri GG, Ann P, Ma L et al (2015) Indigenous bacteria from the gut microbiota regulate host serotonin biosynthesis. Cell 161:264–276. https://doi.org/10.1016/j.cell.2015.02.047

Ye L, Amberg J, Chapman D, Gaikowski M, Liu WT (2014) Fish gut microbiota analysis differentiates physiology and behavior of invasive Asian carp and indigenous American fish. ISME J 8:541–551

Yoshida MA, Tanabe T, Akiyoshi H, Kawamukai M (2022) Gut microbiota analysis of Blenniidae fishes including an algae-eating fish and clear boundary formation among isolated Vibrio strains. Sci Rep 12(1):1–13

Yukgehnaish K, Kumar P, Sivachandran P, Marimuthu K, Arshad A, Paray BA, Arockiaraj J (2020) Gut microbiota metagenomics in aquaculture: factors influencing gut microbiome and its physiological role in fish. Rev Aquac 12(3):1903–1927

Zarkasi KZ, Taylor RS, Abell GC, Tamplin ML, Glencross BD, Bowman JP (2016) Atlantic salmon (Salmo salar L.) gastrointestinal microbial community dynamics in relation to digesta properties and diet. Microb Ecol 71:589–603. https://doi.org/10.1007/s00248-015-0728-y

Zeng A, Tan K, Gong P, Lei P, Guo Z, Wang S et al (2020) Correlation of microbiota in the gut of fish species and water. 3 Biotech 10(11):1–10

Zhai Q, Yu L, Li T, Zhu J, Zhang C, Zhao J, Zhang H, Chen W (2017) Effect of dietary probiotic supplementation on intestinal microbiota and physiological conditions of Nile tilapia (Oreochromis niloticus) under waterborne cadmium exposure. Antonie Van Leeuwenhoek 110:501–513. https://doi.org/10.1007/s10482-016-0819-x

Zhang C, Derrien M, Levenez F, Brazeilles R, Ballal SA, Kim J et al (2016) Ecological robustness of the gut microbiota in response to ingestion of transient food-borne microbes. ISME J 10(9): 2235–2245

Zhang Z, Li D, Refaey MM, Xu W, Tang R, Li L (2018) Host age affects the development of southern catfish gut bacterial community divergent from that in the food and rearing water. Front Microbiol 9:495. https://doi.org/10.3389/fmicb.2018.00495

Zhou Z, Yao B, Romero J, Waines P, Ringø E, Emery M et al (2014) Methodological approaches used to assess fish gastrointestinal communities. In: Merrifield D, Ringø E (eds) Aquaculture nutrition: gut health, probiotics and prebiotics. John Wiley & Sons Ltd., Hoboken

Metabolic Adaptation of Fishes Under Different Consequences of Climate Change

Shivendra Kumar, Maneesh Dubey, and Abhishek Kumar

Abstract

Aquaculture sustainability is affected by climate change which regulated livelihood, nutrition and world food security. The most important contributor to climate change is documented by a human due to deforestation and industries that release GHGs (greenhouse gases) accumulated in the surrounding environment such as methane, nitrous oxide, fluorinated gases and carbon dioxide. Climate change affected fisheries adversely but it is overshadowing the positive one. The effects of climate change on fishes can be directed by water quality parameters such as temperature, dissolve oxygen, pH (acidification) etc. which affected fish physiology and behavioural changes through metabolic adaptation. Due to the changes in climate fishes are adapting to a novel environment like high temperatures (higher to lower latitude or lower to higher latitude), a hypoxic condition due to evolutionary effect and adapting to low pH which is caused by high carbon dioxide released in the environment by human activities. This chapter mainly focuses on how fishes are adapting to the novel climatic condition such as a high or low temperature, hypoxic conditions and low pH through the metabolic activity through enzymatic action (fish physiology) and morphological changes like gill structure to cope with low oxygen and acidification of natural water body.

Keywords

Climate change · Metabolic adaptation · Temperature · Dissolved oxygen · Enzyme activity

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1 Introduction

The aquaculture system includes freshwater, marine and brackish waters, environments scattered under the tropical, subtropical and temperate region. The production of aquaculture depends on water quality parameters, which is affected by climate change such as increasing temperature, and rain pattern (Blanchard et al. 2017; Zolnikov 2019). According to Dabbadie et al. (2018) and FAO (2020), aquaculture sustainability is affected by climate change which regulated livelihood, nutrition and world food security. The most important contributor to climate change is documented by a human due to deforestation (Riphah 2015), which releases GHGs (greenhouse gases) accumulated in the surrounding environment such as methane, nitrous oxide, fluorinated gases and carbon dioxide.

Aquaculture species will need to be adapted or adjusted in their continuing global warming or raising the temperature as studied by Hoffmann and Sgro (2011). There has been cumulative evidence viz. few aquatic animals can manage increasing temperature by acclimatisation through phenotypic plasticity (Salinas et al. 2013). According to Parmesan (2006) in terrestrial and Poloczanska et al. (2013) in marine, species have migrated from lower latitude to higher latitude but few geographical distributions in the majority of species are still unaffected due to rising temperature.

In all three climatic regimes such as tropical, subtropical and temperate regions, the tropical species are mostly prone to climate change since they grow in moderately constant thermal locations (Deutsch et al. 2008). As compared to temperate aquatic species, tropical species have less thermal tolerance (Sunday et al. 2011) and also have less phenotypic plasticity acclimation (Portner and Farrell 2008). Thus, genetic adaptation to climate change probably might be necessary for tropical species through heritable variation in the trait of interest with good selection and evaluation of the evolutionary potential to climate change for the future (Reusch 2014).

2 Climate Change Effects on Fish and Fisheries

Aquatic animals like fishes are ectothermic or poikilothermic animals, and it is regulated by surrounding aquatic climatic factors. Two essential factors in the aquatic environment are biotic and abiotic element. Biotic factors consisted of species composition and availability of food and abiotic factor includes temperature, sea level, salinity, nutrients, availability of oxygen, water current and pH, which all are influenced by climate change. Climate change has both direct (fish physiology, behaviour, reproductive ability, distribution, mortality and growth alteration) and indirect impact (productivity, structure and ecosystem composition related to fish feed) on aquatic organism.

The expected rise in 1.5 °C average global temperature during this century may increase the mortality of most fish, especially cold-water species, such as Atlantic halibut, Salmon and Cod, and intertidal shellfish due to thermal stress (Gubbins et al. 2013). Deviation in species availability and distribution alters species composition of the marine environment due to the increasing temperature of the ocean by global warming (Perry et al. 2005). The geographic distribution of marine organisms is greatly influenced by rising temperatures and is determined by factors such as geomorphology, salinity, stratification, water depth, and ocean currents.

The diversity of fish species has been extensively explored by the collected long-term data series to examine population size and structure and breeding behaviour which is affected by climate change in North Atlantic Oscillation (NAO; Alheit et al. 2005). As a result of climate change, fishes' geographic distribution changes most frequently close to the northern or southern poles, where temperatures are rising at higher latitudes while decreasing at lower latitudes (Beare et al. 2004).

There is little research that has been analysed to examine the changes in the abundance of phytoplankton and zooplankton spring blooms (Wiltshire et al. 2008) and the phenology of the breeding habitat of fish species (Sims et al. 2005). According to Beaugrand et al. (2002), Beaugrand 2004), shifting availability of food for larvae and juveniles probably leads to regime alteration between before and later due to climate change. The observed effects of global warming on fishes are at the different levels of biological organisation (organismal, population, and community ecosystems) and caused by physiological changes at the molecular, cellular, and whole organism levels, and that the long-term impacts of global warming at the ecosystem level will be built on species specific responses (Portner 2001, 2002).

According to the facts above, fish metabolism is impacted by the daily changes in climate, especially increase in temperature. As a result, it is necessary to examine how species adapt to changing environments.

3 Effect of Climate Change on the Metabolic Pathway

Fishes are poikilotherms or ectotherms; therefore their physiology is highly influenced by temperature which affected their metabolic pathway, feeding behaviour, locomotion and energy balance. An increase in 10 °C of aquatic environment temperature can raise a two to threefold metabolic process (Q10) (Willmer et al. 2009). Temperature influences oxygen consumption, cellular respiration and enzymatic reaction (Liu et al. 2019), and heat shock stress induces histopathological changes, rises in Hsp 70 (heat shock protein, indicating thermal stress) as well as a significant alteration in metabolisms. Liu et al. (2019) worked on Lenok (*Brachymystax lenok)* to thermal stress and found suppression of energy metabolism, amino acid catabolism, biosynthesis of glutamate and glutamine that altered nucleotide metabolism and changes in lipid metabolism. Thus, high temperature raises biochemical reactions.

4 Enzymatic Adaptation Due to Consequences of Climate Change

Adaptation of fishes to a new environment, which is changed by climate change, especially rising temperature, is mostly regulated by the acclimation of enzymes to survive and perform normal metabolic pathways. Some metabolic acclimation enzymes exhibit strong compensation, whereas others do not. The enzymes involved in energy release, such as those in the tricarboxylic acid cycle, pentose shunt, electron transport, and fatty acid oxidation, exhibit temperature compensation, whereas the enzymes that are primarily involved in the breakdown of metabolic products exhibit poor or reverse compensation (Prosser 1973) (Fig. 1).

Some of the enzymes exhibit compensation such as Phosphofructokinase, Na-K-ATPase, protease, aminoacyl transferase, NAO-cytochrome reductase, aldolase, lactic dehydrogenase, 6-phosphogluconate dehydrogenase, succinic dehydrogenase, malic dehydrogenase, cytochrome oxidase and succinate-cytochrome C reductase. However, some of the enzymes show no or reverse compensation such as Glucose-6-phosphate dehydrogenase, malic enzyme, lipase, amylase, uricase, allantoinase, alkaline phosphatase, acetylcholine esterase, choline acetyltransferase, Mg-ATPase, D-amino acid oxidase, acid phosphatase, catalase and peroxidase. Differences in kinetics, changes in the proportion of isoenzymes suitable for particular temperatures, and changes in cofactors such as lipids, co-enzymes or other factors such as pH and ions may be important in animals' adjustment to temperature changes.

An increase in standard metabolic rate (SMR) is necessary for routine activity and maintaining life. Low water temperatures minimise nutrient digestibility, increase gut transit time (this is the time between digestion and voided by fish), and let down

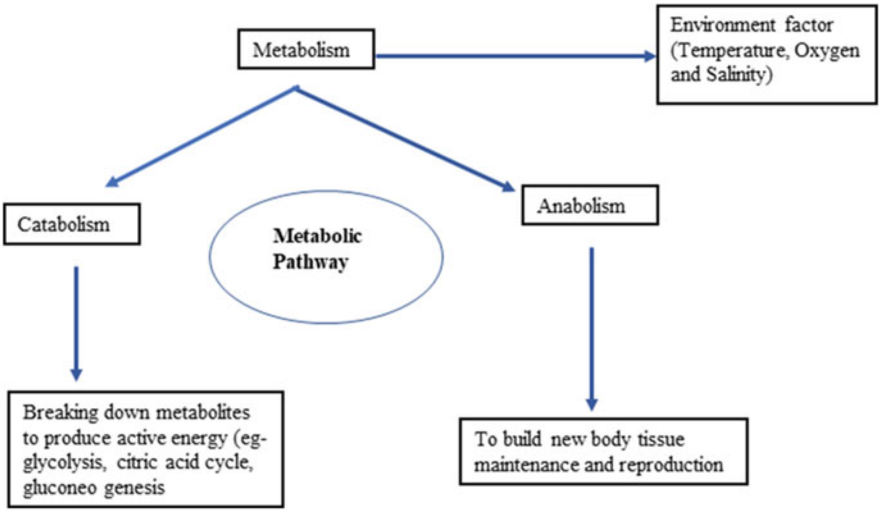


Fig. 1 Overview of a metabolic pathway in fish

gastrointestinal evacuation rates (Miegel et al. 2010). Kumar et al. (2013) reported enhanced enzyme activity due to higher temperature within optimum range and increased enzyme activities that lasted for 3 weeks which supported the growth of *L. rohita.* Solovyev and Izvekova (2016) revealed that the pH of the gastrointestinal tract increases at low temperatures and decreases at high temperatures or during summer. A digestive enzyme of fishes is a temperature-specific adaptation, for example, in cold-water fishes, *Gadus morhua* catalytic efficacy much more in moderate and low temperatures as compared to high temperatures (Stefansson et al. 2017). Fang et al. (2010) revealed that the metabolism of fishes in relation to protein and lipid and digestibility of enzymes is directly influenced by aquatic temperature.

5 Metabolic Adaptation in Temperature Fluctuation

High latitude fishes have less tolerance to fluctuating temperature than low latitude fishes, and mid-latitude fishes have high temperature tolerance because of more seasonal climate variation. If fishes acclimatised to a wide range of temperatures around 20 °C then many variances can be found at lower and upper limits (Portner and Peck 2010).

Juvenile and young adults are less sensitive to fluctuating temperature because of their small body size as compared to larger fishes. Brood fishes or larger-size fishes are highly sensitive than smaller ones to temperature because of more oxygen demand for the oxygen supply to nourish their sperm and eggs (Portner and Farrell 2008). In some fish species, long-term exposure is not possible to lower the limit of temperature, for example, *Sparus aurata* L. cannot be reared at lesser than 10 °C which caused winter syndrome (Domenech et al. 1997).

Oxidative capacities increased in skeletal muscle or fish tissue at low temperatures. The proportion of muscle fibres occupied by mitochondria increases at low temperature, especially in demersal fish species. During evolutionary adaptation to cold temperatures, isolated muscle mitochondria do not show any compensation of protein-specific rates of substrate oxidation. The high volume of mitochondrial number in oxidative muscle during phenotypic low-temperature acclimatisation is found in some species such as *Carassius carassius, Striped bass* and *Morone saxatilis* but it is stable in *Oncorhynchus mykiss.* The role of the endoplasmic reticulum of mitochondria is to scatter oxygen by the muscle fibre and it may be called as the proliferation of mitochondria. Alteration in mitochondrial properties such as cristae, enzymatic balance and membrane phospholipid increases the capacity of oxidation of muscle if mitochondrial volume does not change (Guderley 2004).

For the evolution to a specific range of temperature, fish species inhabit specific thermal habitats. In cold-water fishes for example, Antarctic fish ATPase activity of the myofibrillar protein is fairly high at a low temperature of around 0 °C but it is heat-inactivated at relatively low temperature (Johnston and Goldspink 1975) and it might be a general feature of protein of Antarctic or cold-water fish (Somero 2004).

Wilderbuer et al. (2002) studied climate change that may affect the transport of eggs and larvae amongst spawning and nursery grounds and Sims et al. (2005) found an alteration in spawning migration.

Climate change affected poikilothermic or ectothermic animals and nowadays, it leads to attention on the aquatic animal mechanisms (Sunday et al. 2012; Seebacher et al. 2014). Climate change continues increasing the temperature and fishes are adjusting or acclimating to this novel temperature situation by managing their physiology. Metabolic rate can increase manyfold, that is 10 °C range (Q10 value) but many species can reduce that increased metabolic activity by acclimatisation or adaptation studied by Seebacher et al. (2014). Decreased Q10 after acclimation to heat indicates a reduced sensitivity of metabolic rates in poikilotherms to increasing environmental temperature under climate change scenarios (Sandblom et al. 2014). The acclimation of fishes to high temperatures in most cases does no adopt for coming generation. Fishes can adapt to any metabolic rates at different temperatures in long-term exposure (Clarke and Fraser 2004). Adaptation frequency and degree are varied between species and situations, and the demonstration of fish activity in a warming situation can be measured by standard metabolic rates (SMR) by estimating energy expenditure (Pilakouta et al. 2020).

Temperate climate fishes may have an extended growing season if the temperature increases and it promoted the production of warmer water species such as mussels, oysters, tilapia and Giant tiger prawns (Collins et al. 2020). Many investors installed the hatchery in higher numbers in favourable areas where market opportunities are also profitable, because of declining and degrading natural wild specimens such as spawning grounds, for example, degradation of coral reefs (Bell et al. 2010). Higher temperature may offer to progress in genetic improvement and gives chance to culture new species of aquatic organisms (Gubbins et al. 2013).

6 Metabolic Adaptation in Hypoxia Condition

Continuous pollution created by human action (anthropogenic activity) or by the natural way leads to alteration in species distribution and decreases population size due to unavailability of oxygen (hypoxia) over many years. The depletion of oxygen in the fishes is needed to be adapted to a new hypoxic environment. Some of the fishes have been adapted to low concentrations of oxygen by their evolutionary history which will permit them to cope in a new hypoxic environment which is caused by pollution for survival (Portner and Peck 2010).

According to Coulter (1991), naturally occurring hypoxia is caused by severe stratification (formed layer in water between cold and warm water in the water column and restricts the mixing of oxygen from top to bottom of the lake or other water bodies). Over 400 coastal hypoxic zones (dissolved oxygen, DO: less than mg/L) covering a total area of approximately 250,000 km^2 have been identified throughout the world, many of them in a region that until recently had normal DO levels (normoxic, 7 mg/L) in their bottom waters (Thomas and Rahman 2011). Overstocking of fish is also one of the reasons for hypoxia condition (Boyd and

Schmitton 1999). The hypoxic condition naturally occurs in frozen aquatic environments, due to reduced photosynthesis and decreased intake of oxygen in ice (Van Ginneken 1996). There are extensive reports on hypoxia that is known to hinder the reproductive performance of fishes. A study conducted on Atlantic croakers of the northern Gulf of Mexico continental shelf hypoxic zone showed that there is extensive widespread reproductive disruption, and ovarian masculinization, because of aromatase suppression due to prolonged hypoxia (Thomas and Rahman 2011). Hypoxia acts as endocrine disruptor in fishes, thereby reducing the reproductive ability of fishes.

Depletion of oxygen causes alteration in gill morphology such as reducing the gill surface area and increasing the density of mitochondrial rich cells (MRCs) on the gill lamellae. The proliferation of MRCs on lamellae prevents reduced blood water diffusion and impairs gas transfer (Lin and Sung 2003). Brauner and Berenbrink (2007) revealed that reduced blood water diffusion created osmo-respiratory compromises and is called adaptation. These evolutionary changes transformed fishes to air-breathing fishes which are called adaptation due to low oxygen viz. Lungfishes (Dipnoi) and some modern groups such as Plecomorpha, Ostariophysi and Osteoglossomorpha (Portner and Peck 2010).

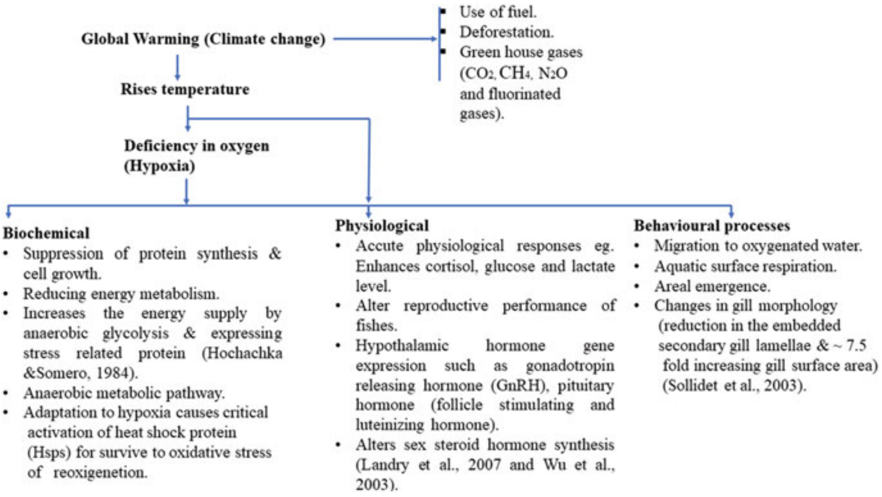
Heat shock protein 90 (Hsp90) is required for the stability and function of HIF-1α. HIF-1α consists of two subunits, ARNT (aryl hydrocarbon nuclear translocator) and HIF-1α, which confers hypoxia sensitivity by binding with ARNT during hypoxic conditions. The translated HIF-1α is stabilised by Hsp90 before binding to ARNT. Hsp70 is also induced in many types of mammalian cells to provide increased resistance to ischemic and hypoxic injury (Polla et al. 1998). Stress protein in mammalian cardiac tissue increases to almost three times baseline levels in response to brief ischemia (Marber et al. 1993). However, in some species of fish, cells or tissues did not express elevated Hsp70 levels in response to hypoxia. During hypoxic conditions, a highly significant induction of Hsp70 was detected in packed blood cells, brain and muscle tissues of juveniles Nile tilapia (Delaney and Klesius 2004). Crucian carp could increase the expression of Hsp70 during anoxia but this response was temperature-dependent.

7 Metabolic Adaptation in a Change in Water pH

The acidic aquatic environment is one of the major issues in the fisheries sector which is mostly caused by high release of CO_2 (lowering the pH) that is created by human activity. Earlier evidence exhibits that the oceanic surface was slightly alkaline and now it is already becoming more acidic, this is called ocean acidification. Ocean acidification is considered to be a serious threat to marine species, especially calcifying species that require carbonate ions to form their shells and skeletons (Hoegh-Guldberg et al. 2007). Elevated pCO_2 can also have a direct physiological effect on aquatic species through disruption of acid-base balance and limiting oxygen supply (Portner et al. 2004; Portner and Farrell 2008). Increased pCO_2 in tissue causes acidosis (lowering of pH and accumulation of bicarbonate), which can be detrimental to many cellular processes, including protein synthesis, enzymatic function and oxygen transport (Portner et al. 2004). Fish compensate for acidosis by acid-base equivalent ion transport from the body to the environment, mostly across the branchial epithelium, and to a lesser extent, via the kidneys and intestine (Claiborne et al. 2002). Some of the studies showed that sperm motility is arrested by a mild increase in pCO_2 (Inaba et al. 2003). The sensitivity of fish eggs to elevated CO_2 varies markedly between species, but species tested to date typically have 24-h LC_{50} values well above 10,000 ppm CO_2 (Ishimatsu et al. 2008). One of the potential impacts of acidification can reduce aerobic capacity and cause tissue hypoxia in fishes (Portner and Farrell 2008).

Acidification of water is also experienced in the inland areas in the form of acid rain. The phenomenon called acid rain results from industrial activities where sulfuric and nitric acids are produced by the release of sulfuric oxides (SO_X) and nitrogen oxides (NO_X) into the atmosphere. Acid rain induces the acidification of inland waters which results in damage to aquatic ecosystems, including fish. Most natural aquatic environments have a pH of 6.0–9.0 and most fishes can live in water in this range (Hargis 1976). Changes in the pH of the environment can alter the enzymatic activities or electrolyte composition of body fluids, which cause acute stress because fishes are poor regulators of internal pH (Packer and Dunson 1970; Eddy 1976). Changes in pH also affected feed intake and metabolism of fish. Reduced feeding and depressed growth in brook trout (*Salvelinus fontinalis)* (Tam and Zhang 1996) and Arctic charr (*Salvelinus alpinus*) have been reported at low pH due to consequences of suppression of somatotrope secretory activity (Mackett et al. 1992) (Fig. 2).

Effects of pH on aquatic animals mostly depend on adaptation or acclimation. If it increases progressively to pH 9.5 for 6 h then it is lethal to rainbow trout and if not



- Use of fuel.
- Deforestation.
- Green house gases (CO_2, CH_4, N_2O and fluorinated gases).

Biochemical

- Suppression of protein synthesis & cell growth.
- Reducing energy metabolism.
- Increases the energy supply by anaerobic glycolysis & expressing stress related protein (Hochachka &Somero, 1984).
- Anaerobic metabolic pathway.
- Adaptation to hypoxia causes critical activation of heat shock protein (Hsps) for survive to oxidative stress of reoxigenetion.

Physiological

- Accute physiological responses eg. Enhances cortisol, glucose and lactate level.
- Alter reproductive performance of fishes.
- Hypothalamic hormone gene expression such as gonadotropin releasing hormone (GnRH), pituitary hormone (follicle stimulating and luteinizing hormone).
- Alters sex steroid hormone synthesis (Landry et al., 2007 and Wu et al., 2003).

Behavioural processes

- Migration to oxygenated water.
- Aquatic surface respiration.
- Areal emergence.
- Changes in gill morphology (reduction in the embedded secondary gill lamellae & ~ 7.5 fold increasing gill surface area) (Sollidet et al., 2003).

Fig. 2 Biochemical, physiological and behavioural changes due to hypoxia condition raised more than 9.3 at the same time then they only lose their appetite (Murray and Ziebell 1984). Rainbow trout can adapt to pH as high as 9.8 if acclimation time progressively increases to 5 days. Low pH can alter the energy metabolism, alteration in tissue glycogen level, decrease tissue adenylate energy charge and increase plasma glucose concentration. Enzymatic activity (membrane-bound gill sodium and potassium ion ATPase) decreases at low pH if salmonids challenge acidic water pH.

It has been also revealed that sub-lethal acid stress affects the reproduction of fish. If mature salmonid fishes are exposed to sulphuric acid water of pH 4.5–5.0, inhibition of development and increases in malformation are observed in the embryos of their offspring (Ikuta et al. 1999). When mature rainbow trout were reared in pH 4.5 just before spawning, the eying rate (index indicating normal development) of embryos from females exposed to acid decreased drastically, and the malformation rate of embryos produced with sperm from males exposed to acid increased in a time-dependent manner, even if the embryos were cultured in neutral water after fertilisation.

In general, various physiological and behavioural impediments by water acidification in fish are as follows:

1. Extremely slight acidification at pH 6 and lower ranges inhibit homing migration and/or spawning behaviour.
2. Sub-lethal acid stress at pH 5 and lower ranges stimulate avoidance of acidic areas or induce failure of immune and reproductive functions via the alteration of physiological mechanisms, including the actions of endocrine factors.
3. Acidification in the range of pH 4 rapidly affects the acid-base regulatory function of gill chloride cells, resulting in mortality due to the efflux of NaCl from body fluid.

8 Conclusion

NOBEL peace prize-winning Intergovernmental Panel on Climate Change (IPCC) report and the documentary “An Inconvenient Truth” on AI Gore’s campaign to make the issue of global warming a recognised problem worldwide was an eye-opener to its impact on the habitat of earth. The major prediction was the rise in global mean temperature from 1.5 to 4.5 °C over the next half-century would lead to consequences such as rising sea levels, increasing extreme weather events, erosion of coastal areas, and melting of ice caps leading to declining water quality, biodiversity and yield of fishes. The global average air temperature near the Earth’s surface rose 0.74 °C during the last 100 years. Global surface temperature is likely to increase by 1.4–4.5 °C by 2100 which creates global warming and its related risk to health such as food security, economic development, human security, water supply and livelihood. Zolnikov (2019) studied adaptation and reported that mitigation is the only way to deal with climate change with its resilience as successfully as possible, and it might be helping to prepare the farming communities, populations and ecosystems. The mitigation of climate change involves the reduction of anthropogenic activity which is mostly by greenhouse gases (GHGs) such as carbon dioxide by humans which accounts for more than 60% (IPCC 2014; Environmental Protection Agency 2016).

References

Alheit J, Mollmann C, Dutz J, Kornilovs G, Loewe P, Mohrholz V, Wasmund N (2005) Synchronous ecological regime shifts in the central Baltic and the North Sea in the late 1980s. ICES J Mar Sci 62:1205–1215

Beare DJ, Burns F, Greig A, Jones EG, Peach K, Kienzle M, McKenzie E, Reid DG (2004) Long-term increases in prevalence of North Sea fishes having southern biogeographic affinities. Mar Ecol Prog Ser 284:269–278

Beaugrand G (2004) The North Sea regime shift: evidence, causes, mechanisms and consequences. Prog Oceanogr 60:245–262

Beaugrand G, Reid PC, Ibanez F, Lindley JA, Edwards M (2002) Reorganization of North Atlantic marine copepod biodiversity and climate. Science 296:1692–1694

Bell J, Batty M, Ganachaud A, Gehrke P, Hobday A, Hoegh-Guldberg O et al (2010) Preliminary assessment of the effects of climate change on fisheries and aquaculture in the Pacific. In: Gillett R (ed) Fisheries in the economies of the Pacific Island Countries and Territories, Pacific studies series. Asian Development Bank, Manila, pp 451–469

Blanchard JL, Watson RA, Fulton EA, Cottrell RS, Nash KL, Bryndum-Buchholz A et al (2017) Linked sustainability challenges and trade-offs among fisheries, *aquaculture and agriculture*. Nat Ecol Evol 1:1240–1249

Boyd CE, Schmitton HR (1999) Achievement of sustainable aquaculture through environmental management. Aquac Econ Manag 3(1):59–70

Brauner CJ, Berenbrink M (2007) Gas transport and exchange. In: McKenzie DJ, Farrell AP, Brauner CJ (eds) Primitive fishes, fish physiology, pp 213–282

Claiborne JB, Edwards SL, Morrison-Shetlar AI (2002) Acid-base regulation in fishes: cellular and molecular mechanisms. J Exp Zool 293:302–319

Clarke A, Fraser KPP (2004) Why does metabolism scale with temperature? Funct Ecol 18(2):243–251

Collins C, Bresnan E, Brown L, Falconer L, Guilder J, Jones L et al (2020) Impacts of climate change on aquaculture. MCCIP Sci Rev 2020:482–520

Coulter GH (1991) Lake Tanganyika and its life. Oxford University Press, New York

Dabbadie L, Aguilar-Manjarrez JJ, Beveridge MCM, Bueno PB, Ross LG, Soto D (2018) Chapter 20: effects of climate change on aquaculture: drivers, impacts and policies. FAO, Rome

Delaney MA, Klesius PH (2004) Hypoxic conditions induce Hsp70 productionin blood, brain and head kidney of juveniles Nile tilapia *Oreochromis niloticus*. Aquaculture 236:633–644

Deutsch CA, Tewksbury JJ, Huey RB, Sheldon KS, Ghalambor CK, Haak DC, Martin PR (2008) Impacts of climate warming on terrestrial ectotherms across latitude. Proc Natl Acad Sci U S A 105:6668–6672

Domenech A, Fernandez-Garayzabal JF, Lawson P, Garcıa JA, Cutili MT, Blanco M, Gibello A, Moreno M, Collins MD, Domíguez L (1997) Winter disease outbreak in sea bream (*Sparus aurata*) associated with *Pseudomonas anguillieptica* infection. Aquaculture 156:317–326

Eddy FB (1976) Acid-base balance in rainbow trout (*Salmo gairdneri*) subjected to acid stresses. J Exp Biol 64:159–171

Environmental Protection Agency (2016) Sources of greenhouse gas emissions. Retrieved from: https://www.epa.gov/ghgemissions/sources-greenhouse-gasemissions

Fang J, Tian X, Dong S (2010) The influence of water temperature and ration on the growth, body composition and energy budget of tongue sole (*Cynoglossus semilaevis*). Aquaculture 299(1–4):106–114

FAO (2020) The state of world fisheries and aquaculture 2020. Sustainability in action. FAO, Rome

Gubbins M, Bricknell I, Service M (2013) Impacts of climate change on aquaculture. MCCIP Sci Rev:318–327

Guderley H (2004) Metabolic responses to low temperature in fish muscle. Biol Rev 79:409–427

Hargis JR (1976) Ventilation and metabolic rate of young rainbow trout (*Salmo gairdneri*) exposed to sublethal envrionmental pH. J Exp Zool 196:39–44

Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P et al (2007) Coral reef under rapid climate change and ocean acidification. Science 318:1737–1742

Hoffmann AA, Sgro CM (2011) Climate change and evolutionary adaptation. Nature 470:479–485

Ikuta K, Vada T, Kitamura S, Branch N, Ito F, Yamagichi M, Nishimura T, Kaneko T, Nagae M, Ishimatsu A, Iwata M (1999) Effects of acidification on fish reproduction. UJNR technical report no. 28, pp 39–45

Inaba K, Dreanno C, Coson J (2003) Control of flatfish sperm motility by CO_2 and carbonic anhydrase. Cell Motil Cytoskeleton 55:174–187

IPCC (2014) Climate change 2014: synthesis report. Contribution of working groups I, II and III to the fifth assessment report on the intergovernmental panel on climate change. In: Core writing team, Pachauri RK, Meyer LA (eds). Intergovernmental Panel on Climate Change, Geneva. 151 pp. Available online at: http://www.ipcc.ch/pdf/assessmentreport/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf

Ishimatsu A, Hayashi M, Kikkawa T (2008) Fishes in high-CO_2, acidified oceans. Mar Ecol Prog Ser 373:295–302

Johnston IA, Goldspink G (1975) Thermodynamic activation parameters of fish myofibrillar ATPase enzyme and evolutionary adaptations to temperature. Nature 257:620–622

Kumar S, Sahu NP, Pal AK, Saravanan S, Priyadarshi H (2013) Short term exposure to higher temperature triggers the metabolic enzyme activities and growth of fish *Labeo rohita* fed with high protein diet. Aquac Nutr 19:186–198

Lin HC, Sung WT (2003) The distribution of mitochondria-rich cells in the gills of air-breathing fishes. Physiol Biochem Zool 76:215–228

Liu Y, Liu J, Ye S et al (2019) Global metabolic responses of the lenok (*Brachymystax lenok*) to thermal stress. Comp Biochem Physiol D 29:308–319

MacKett DB, Tam WH, Fryer JN (1992) Histological changes in insulin-immunoreactive pancreatic beta cells, and suppression of insulin secretion and somatotrope activity in brook trout (*Salvelinus fontinalis*) maintained on reduced food intake or exposed to acidic environment. Fish Physiol Biochem 10:229–243

Marber MS, Latchman DS, Walker JM, Yellon DM (1993) Cardiac stress protein elevation 24 hours after brief ischemia or heat stress is associated with resistance to myocardial infarction. Circulation 88(3):1264–1272

Miegel RP, Pain SJ, van Wettere WHEJ et al (2010) Effect of water temperature on gut transit time, digestive enzyme activity and nutrient digestibility in yellowtail kingfish (*Seriola lalandi*). Aquaculture 308(3–4):145–151

Murray CA, Ziebell CD (1984) Acclimation of rainbow trout at high pH to prevent stocking mortality in summer. Prog Fish Cult 46:176–179

Packer HK, Dunson WA (1970) Effects of low environmental pH on blood pH and sodium balance of brook trout. J Exp Zool 174:65–72

Parmesan C (2006) Ecological and evolutionary responses to recent climate change. Annu Rev Ecol Evol Syst 37:637–669

Perry AL, Low PJ, Ellis JR, Reynolds JD (2005) Climate change and distribution shifts in marine fishes. Science 308:1912–1915

Pilakouta N, Killen SS, Kristjansson BK, Skulason S, Lindstrom J, Metcalfe NB, Parsons KJ (2020) Multigenerational exposure to elevated temperatures leads to a reduction in standard metabolic rate in the wild. Funct Ecol 34:1205–1214

Polla BS, Bachelet M, Elia G, Santoro GM (1998) Stress proteins in inflammation. Ann N Y Acad Sci 851:75–85

Poloczanska ES, Brown CJ, Sydeman WJ et al (2013) Global imprint of climate change on marine life. Nat Clim Chang 3:919–925

Portner HO (2001) Climate change and temperature dependent biogeography: oxygen limitation of thermal tolerance in animals. Naturwissenschaften 88:137–146

Portner HO (2002) Climate change and temperature dependent biogeography: systemic to molecular hierarchies of thermal tolerance in animals. Comp Biochem Physiol A 132:739–761

Portner HO, Farrell AP (2008) Ecology: physiology and climate change. Science 322:690–692

Portner H, Peck M (2010) Climate change effects on fishes and fisheries: towards a cause-and-effect understanding. J Fish Biol 77:1745–1779

Portner HO, Langenbuch M, Reipschlager A (2004) Biological impact of elevated ocean CO_2 concentrations: lessons from animal physiology and earth history. J Oceanogr 60:705–718

Prosser CL (ed) (1973) Comparative animal physiology, 3rd edn. W.B. Saunders Company, Philadelphia, 1011 p

Reusch TBH (2014) Climate change in the oceans: evolutionary vs. phenotypically plastic responses of marine animals and plants. Evol Appl 7:104–122

Riphah SU (2015) Global warming: causes, effects and solutions. Durreesamin J 1:1–7

Salinas S, Brown SC, Mangel M, Munch SB (2013) Non-genetic inheritance and changing enviromnents. Non-Genetic Inherit 1:38–50

Sandblom E, Gräns A, Axelsson M, Seth H (2014) Temperature acclimation rate of aerobic scope and feeding metabolism in fishes: implications in a thermally extreme future. Proc R Soc B Biol Sci 281:20141490–20141490

Seebacher F, White CR, Franklin CE (2014) Physiological plasticity increases resilience of ectothermic animals to climate change. Nat Clim Chang 5:61–66

Sims DW, Wearmouth VJ, Genner MJ, Southward AJ, Hawkins SJ (2005) Low-temperature-driven early spawning migration of a temperate marine fish. J Anim Ecol 73:333–341

Solovyev MM, Izvekova GI (2016) Seasonal changes in pH values in the intestine of fish from Lake Chany (West Siberia). Inland Water Biol 9(4):400–404

Somero GN (2004) Adaptation of enzymes to temperature: searching for basic “strategies”. Comp Biochem Physiol B Biochem Mol Biol 139:321–333

Stefansson B, Sandholt GB, Gudmundsdottir Á (2017) Elucidation of different cold-adapted Atlantic cod (*Gadus morhua*) trypsin X isoenzymes. Biochim Biophys Acta 1865(1):11–19

Sunday JM, Bates AE, Dulvy NK (2011) Global analysis of thermal tolerance and latitude in ectotherms. Proc R Soc B Biol Sci 278:1823–1830

Sunday JM, Bates AE, Dulvy NK (2012) Thermal tolerance and the global redistribution of animals. Nat Clim Chang 2:1–5

Tam WH, Zhang X (1996) The development and maturation of vitellogenic oocytes, plasma steroid hormone levels, and gonadotrope activities in acid-stressed brook trout (*Salvelinus fontinalis*). Can J Zool 74:587–594

Thomas P, Rahman SM (2011) Extensive reproductive disruption, ovarian masculinization and aromatase suppression in Atantic croaker in the northern Gulf of Mexico hypxic zone. Proc R Soc B 279:28–38

Van Ginneken VJT (1996) Influence of hypoxia and acidification on the energy metabolism of fish. An in vivo 31P-MNR and calorimetric study. PhD thesis. State University of Leiden, Leiden

Wilderbuer TK, Hollowed AB, Ingraham WJ, Spencer PD, Conners ME, Bond NA, Walters GE (2002) Flatfish recruitment response to decadal climate variability and ocean conditions in the eastern Bering Sea. Prog Oceanogr 55:235–247

Willmer P, Stone J, Johnston I (2009) Environmental physiology of animals. Wiley-Blackwell, Malden, MA, USA

Wiltshire KH, Malzahn AM, Wirtz K, Greve W, Janisch S, Mangelsdorf P, Manly B, Boersma M (2008) Resilience of North Sea phytoplankton spring bloom dynamics: an analysis of long term data at Helgoland Roads. Limnol Oceanogr 53:1294–1302

Zolnikov TR (2019) Global adaptation and resilience to climate change. Palgrave studies in climate resilient societies (Bern)

Argulus Parasitism in Aquaculture: An Elevated Temperature Scenario

Rajive Kumar Brahmchari, Saurav Kumar, Pushpa Kumari, and Kundan Kumar

Abstract

Argulus is a major ectoparasite of fish, capable of causing a substantial economic loss through disease outbreaks, posing a serious threat to global fish farming. Interactions between hosts, parasites, and their environment, particularly temperature, determine the severity and manifestation of disease. The consequences of increased water temperature on *Argulus* parasitism as a result of climate change are poorly understood in terms of process and mechanism, but these changes are likely to reflect on both altering host pools and changing competitive interactions. One of the most obvious outcomes of changing thermal regimes is a shift in the spatiotemporal distribution of *Argulus* due to their fastened life-history traits, which may increase host vulnerability to other diseases and cumulative mortality among farmed fish. As a result, these parasites will likely experience a short generation period because their life-history traits are completed more rapidly. Additionally, it is also anticipated to have the impact of these climatic changes on the physiology, immunology, behavior, and parasite avoidance strategies of fish

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may result in ecosystem-level alterations. Finally, such findings aid in predicting host-parasite dynamics and assisting in the development of appropriate management measures to improve animal welfare and reduce loss in the aquaculture sector.

Keywords

Argulus · Fish ectoparasite · Temperature · Climate change · Life-history traits · Aquaculture

1 Introduction

Aquaculture has grown remarkably over the past five decades and accounts for half the world's fish food supply. As this sector intensifies to endure the global demands, cultured fish are being subjected to a growing number of stressors (Lewin et al. 2006; Wedemeyer 1997). Such circumstances stimulate and exacerbate the transmission of pathogens and disease outbreaks, reinforcing parasitism, arguably the most significant barrier to the long-term expansion of the aquaculture sector (Granada et al. 2016). Global warming is changing the earth's environment and aquatic system with devastating consequences. Although its consequences have previously been concentrated on terrestrial animals, its impact on aquatic species has received less attention (Reid et al. 2019). Fish and shellfish being ectotherms, temperature plays a critical role in their growth and survival since it directly influences their metabolic rate, oxygen demand, immunity, physiology, and reproduction (Shahjahan et al. 2017; Ngoan 2018; Alfonso et al. 2021). It has an equal impact on associated parasites and diseases, which can significantly alter infection dynamics. Higher ambient temperatures often result in a shorter generation period for parasites because their life-history traits are completed more rapidly; however, each trait might respond to temperature differently, resulting in trade-offs (Andersen and Buchmann 1998; Soleng et al. 1998; Sahoo et al. 2013a). Climate models have already illustrated that global climate change will be associated with more frequent temperature extremes and a rise in average temperatures of 1–4 °C by 2100 (IPCC 2015; Masson-Delmotte et al. 2018). Further, this temperature shift is expected to significantly impact host-parasite interactions (Altizer et al. 2013; Lafferty and Shaw 2013; Morley and Lewis 2014; Brunner and Eizaguirre 2016; Cohen et al. 2019; Stensgaard et al. 2019; Poulin 2020). Those parasites for which temperature increases do not exceed their lethal threshold may be predicted to increase in intensity and disease in infected hosts for three reasons since the higher temperatures contribute to (a) increased parasite metabolism, (b) increased oxygen stress on hosts, and (c) expanded transmission windows (Byers 2021). Thus, temperature changes can directly affect parasites through the ambient environment or indirectly through effects on host factors such as distribution, behavior, physiology, and mortality (Marcogliese 2001; Callaway et al. 2012).

Parasites on aquatic animals, like all other organisms, have optimal temperatures for completing their life cycles (Marcogliese 2001). If the optimal temperature windows are extended during the season, it will likely provide a prolonged period for parasitic infections, potentially leading to more parasite generations throughout the season (Callaway et al. 2012). Elevated ambient temperature can be an impending factor in increasing parasite metabolism, resulting in more transmission stages produced, higher parasite fitness, and faster disease spread in a single outbreak (Lõhmus and Björklund 2015). Both of these factors may contribute to the increased prevalence of a disease. Instead, the rise in temperature beyond the thermal tolerance will negatively affect host-parasite trade-offs. This could lead to a reduction in the prevalence of such diseases (Karvonen et al. 2010). Higher temperatures may directly impact the severity and nature of pathology experienced by hosts because they affect the rate of development of individual parasite stages and may influence their number or final size within the host (Paull and Johnson 2011; Callaway et al. 2012).

Argulus spp., commonly referred to as fish lice, are crustacean ectoparasites on fish and responsible for significant economic losses in both marine and freshwater systems. These are one of the most visible parasite groups afflicting fish production (Walker et al. 2004; Hakalahti et al. 2008; Costello 2009; Saurabh and Sahoo 2010; Kumar et al. 2012; Kumari et al. 2019; Sahoo et al. 2012, 2013a, b, 2021). Higher temperatures have been connected to outbreaks (Hakalahti et al. 2004; Shimura 1983; Harrison et al. 2006), with modeling of marine sea lice epidemic potential being higher at elevated temperatures (Groner et al. 2014). Although an increasing number of examples of host-parasite interactions modified by climate change exist in the literature, empirical data on how the temperature affects the overall dynamics of *Argulus* spp. are still lacking. Thus, this chapter aimed to appraise the published findings on the effect of temperature on *Argulus* development, maturity, and parasitism. This is indispensable if we are to forecast infection patterns and build more effective management strategies.

2 General Description of *Argulus*

Argulus are obligate ectoparasites of fish and a member of a large group of brachyuran crustaceans; however, they can be found swimming freely in the water column in search of a new host, mates, or when females separate from their hosts to lay eggs (Mikheev et al. 2015). *Argulus* can cause epizootics leading to massive mortalities; however, the most typical problem caused by this is loss of appetite and the consequent state of extensively infected fish. This parasite is generally noticeable on the caudal fin, skin, chin, and other fins of infested fish (Yildiz and Kumantas 2002). They spread quickly and feed upon mucus, epidermal tissue, and blood from the host, causing ulceration and immunological suppression as well as secondary infection with bacteria and fungus (Saurabh et al. 2011; Kar et al. 2017). Further, this parasite may act as a carrier to transmit other fish pathogens to the host body like spring viremia of carp virus (SVCV), larval nematodes (dracunculoid and skrjabillanid), and the fungus *Saprolegnia* (Gresty et al. 1993; Avenant-Oldewage 2001; Ahne et al. 2002; Hadfield and Smit 2019). In mild infestation with *Argulus*, fish without visible lice may show nonspecific signs, including pinpoint hemorrhages, reduced feeding, avoidance of swimming into the column, increased mucus production, and fish flashing, rubbing their bodies on the surface owing to irritation or eliminating parasites adhered to their bodies (Steckler and Yanong 2012).

3 Effects of Changing Thermal Regimes on *Argulus* Life-History Traits

The life-history traits of a parasite having a direct life cycle are inherently linked to overriding abiotic environmental factors such as rising temperature, which affects the pace of growth, body size, maturity, fecundity, and parasite life span (Tinsley et al. 2011). Such parasites require their hosts to be alive long enough for them to reproduce and usually die when a predator eats the host. These parasites typically benefit from not putting their hosts at risk of predation and from not over-exploiting them before they mature (Barber et al. 2001). On the other hand, a temperature shift may increase the energetic demands and growth rates of parasites or increase the number of hatched parasites, resulting in an "involuntary" over-exploitation of the host (Lõhmus and Björklund 2015). Several studies have elucidated the effects of temperature variations on different life-history traits of *Argulus* (Hakalahti et al. 2006; Harrison et al. 2006; Walker et al. 2011a; Taylor et al. 2009a, b; Koyun 2011; Sahoo et al. 2013a; Hunt and Cable 2020).

The *Argulus* life cycle completes 30–60 days on average (Fig. 1); however, the actual duration depends on the argulid species and the water temperature (Steckler and Yanong 2012), and they reproduce rapidly at a *temperature* range of 20–28 °C. Adult female lay their eggs off the host on firm surfaces such as rocks, glasses, and wood logs, mainly on a vertical face, in rows attached by a gelatinous material that appears to harden on contact with water (Shafir and Van As 1986; Rahman 1995). Three developmental stages follow this: the first is the development of eye pigmentation—jet black large-sized two spots near one end of the egg, the second is the development of thoracic appendages and distinct body characteristics, and the third is the movement of the embryo within 24–48 h before hatching. The larvae hatch as "metanauplius," which possess a pre-oral spine and mouth tube, indicating that it is a feeding stage despite its physical differences from the adult (Rushton-Mellor and Boxshall 1994; Avenant-Oldewage and Lutsch 1995).

Once they find and attach to a host, they go through a series of molts (11 molts or 12 "stages" in *A. foliaceus*) until they reach sexual maturity, which roughly takes 30–40 days after hatching (Steckler and Yanong 2012). The length of the larval phase is highly variable and possibly determined by temperature. Further, different abiotic and biotic factors influence the distribution of *Argulus* by affecting its behavior, ecology, and physiology (Fig. 2).

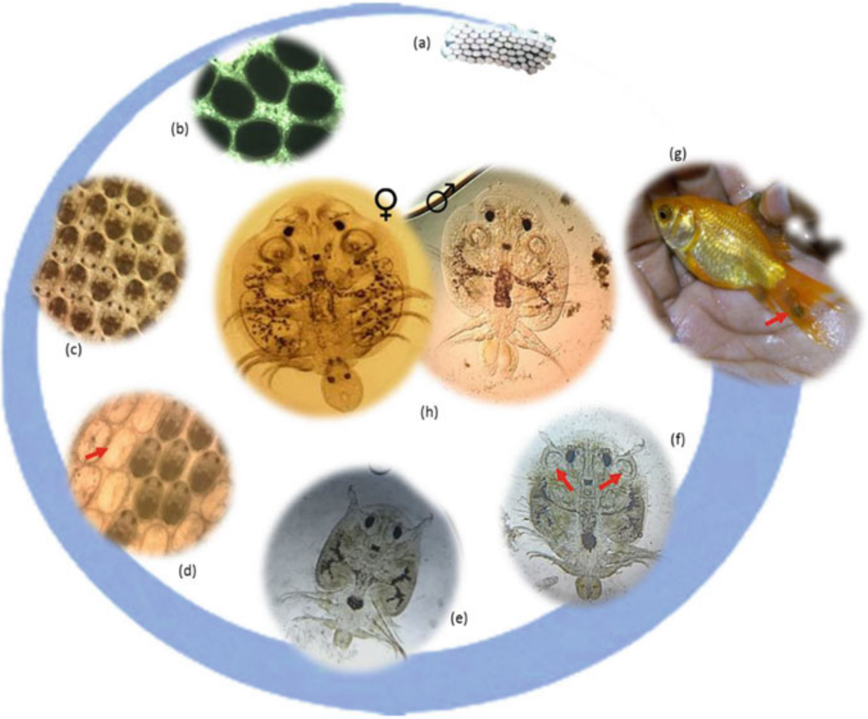

Fig. 1 Egg and larval development of *Argulus japonicas* (under low magnification). (**a**) Egg clutches laid on the substratum; (**b**) 1-day-old eggs with elliptical shape; (**c**) 5–11-day-old eggs with distinct eyespots and developing embryo, shows movements from day 9 to 11 before it hatches; (**d**) a string of eggs demonstrating asynchronous development, contains some fully formed embryos ready to hatch and a few clear eggs (red arrow) showing that embryos have already hatched; (**e**) embryo hatched into metanauplii on the 12th day, with distinct eyes, antennae, and fused abdominal appendages; (**f**) 15-day-old copepodid with free abdominal appendages, the emergence of a distinct abdominal region, the chelated legs start transforming to sucker (red arrow) with growing branchial chamber; (**g**) parasitized goldfish; (**h**) male and female *Argulus*

3.1 Effect on *Argulus* Life Span

Argulus responds positively to increasing temperature with faster incubation and growth. Hunt and Cable (2020) observed that at higher temperatures, the life span of *A. foliaceus* off the host was reduced, potentially affecting infection success. The survival of this parasite on or off the host was unaffected even by a 10 °C temperature variation (24 °C vs. 14 °C), demonstrating its tolerance to temperature variations. Furthermore, egg development, as well as larval growth on hosts, were significantly faster at 24 °C compared to 14 °C, implying that *A. foliaceus* would have a shorter generation time at higher temperatures due to faster maturation and egg development. While fast life-history traits may help parasites to maximize their fitness by quickly exploiting hosts for resources necessary for their survival, they

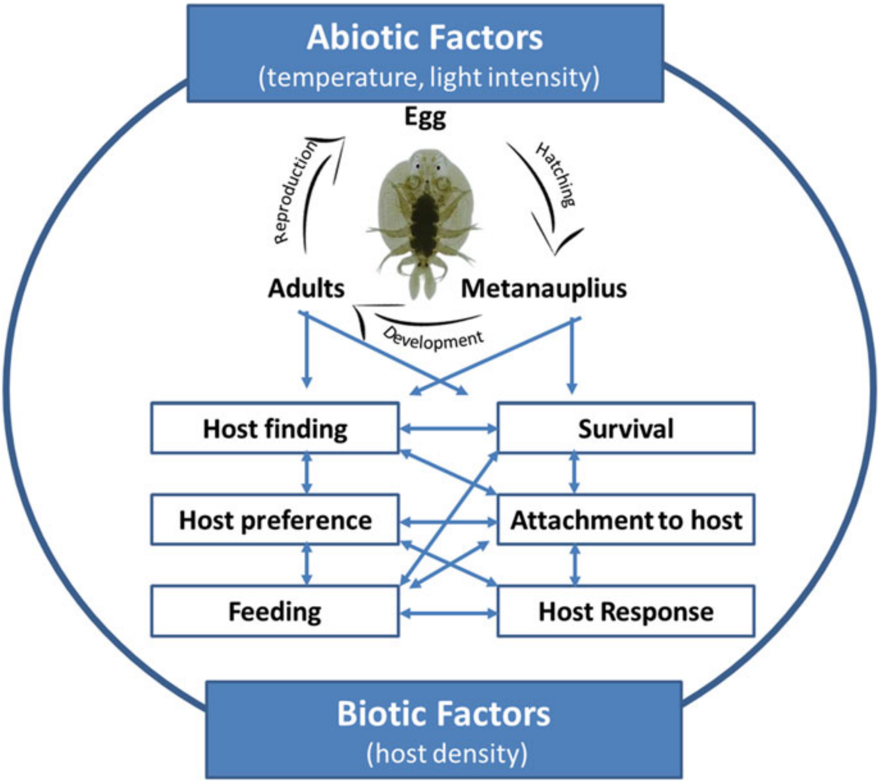

Fig. 2 *Argulus* distribution is influenced by abiotic and biotic factors that influence its behavior, ecology, and physiology. The key attributes of the life cycle of metanauplius and adult parasite maturation/reproduction, as well as how these relate to one another, are shown in boxes. (Modified from Walker 2008)

may also limit infection depending on the population densities of the host; for example, in nematodes, higher host abundance benefits parasites with fast infection rates whereas the low abundance of host favors parasites with slower infection rates (Crossan et al. 2007). However, increasing temperatures may not always be beneficial, and the advantages of being a faster egg development period are nullified as the number of eggs hatching into free-swimming larvae is substantially reduced (van Dijk and Morgan 2008).

The distribution of parasites in hosts is often aggregated, with a few hosts harboring a large number of parasites and the rest being parasite-free. *Argulus* typically exhibit such a pattern within host populations (Bandilla et al. 2005; Walker et al. 2008), which is crucial for their reproductive success (Mikheev et al. 2015). Hunt and Cable (2020) observed higher density of *A. foliaceus* on the host led to lower parasite growth, implying that parasite populations may exhibit reduced growth as aggregation increases. When it comes to parasite location on the host, parasites migrate from feeding on fins to the host body as they grow and the temperature rises. When *A. foliaceus* attained a length of 2.0–2.4 mm (7th developmental stage, when mouth tube is fully developed; Rushton-Mellor and Boxshall 1994), they moved to the body, indicating the hematophagous stage. Juveniles feed only on mucous and skin epithelial cells, while hematophagous adults inflict greater damage to the host and increase the risk of subsequent infections (Bandilla et al. 2006; Walker et al. 2011b).

Hakalahti et al. (2006) observed two types of eggs laid by female *A. coregoni* depending on the ambient environmental conditions: (a) eggs that hatch right after the requisite incubation period and (b) diapausing eggs that hatch later in the season and show delayed hatching. Facultative diapause is a common strategy adopted by many organisms that live in habitats with erratic season lengths. It is often a maternally regulated trait that allows additional generations to emerge when conditions are favorable or undergo diapause when conditions are not favorable (Lõhmus and Björklund 2015). This life-history trait most likely gives *A. coregoni* the ability to respond to longer-lasting growth seasons by shifting from a one-generation to a two-generation population cycle, resulting in more rapid parasite population growth and, inevitably, increased parasite problems in fish (Hakalahti et al. 2006).

3.2 Effect on Egg-Laying Patterns by *Argulus*

The temperature may influence egg-laying patterns of *Argulus*, but there is so far no conclusive evidence for these trends at this time. Egg-laying by *Argulus* typically begins at water temperatures between 14 and 16 °C (Hogans 1994). At temperatures below 8 °C, the parasites stop growing, encase themselves in mucus, and remain on the host until warmer water temperatures arrive (Bauer et al. 1973).

Harrison et al. (2006) looked into the seasonal and vertical patterns of egg-laying by *A. foliaceus*, presuming that water temperature plays a role in influencing egg-laying distribution patterns. Early in the summer, egg-laying was mostly observed in the top 1 m of the water column; however, with the rise in temperature, a significant shift to deep water with egg clutches being laid at depths of up to 8.5 m. Similarly, Taylor et al. (2009a) also found that the depth of egg-laying by *A. foliaceus* varies throughout the year in trout fisheries, commencing in the upper water layers at the beginning of the season and then going deeper as the season advances and the water temperature rises. Thus, it is possible to speculate that factors such as temperature directly influence the depth and location of egg-laying. Taylor et al. (2009a), on the other hand, contend that egg-laying habitats are not actively selected, but rather determined by the habitat usage of the host fish, which would reduce the distance parasite must travel to lay eggs and increases the possibility of infection success since the juvenile parasites would emerge in close proximity to potential hosts. Further, Sahoo et al. (2013a, b) assessed the depth and pattern of egg-laying activity by *A. siamensis* in carp pond by placing bamboo poles vertically at various locations to provide substratum for egg-laying. The middle zone of the pole had the most eggs laid, followed by the upper and lower zones. This supports the hypothesis of Taylor et al. (2009a) because most egg clutches were collected from the middle zone, which also happens to be the habitat of *L. rohita*, the most preferred host of *A. siamensis*.

3.3 Effect on Egg Development and Hatching Success

The time required for Argulus eggs to hatch varies depending upon species and more specifically on temperature (Table 1). Eggs of *A. japonicus* hatch in just 10 days at

Table 1 Effect of temperature on egg incubation period and hatching rate in some common freshwater *Argulus* species

Species	Temperature (in °C)	Egg incubation period (in days)	Hatching rate (in %)	References
Argulus japonicus	10	Nil	Nil	Shafir and van As (1986)
	15	61	18	
	20	28	45	
	25	17	55	
	30	13	40	
	35	10	28	
Argulus foliaceus	19–22	25–51	76	Pasternak et al. (2000)
	5	25–240 (at 5 °C for 5 months, then moved to 20 °C)	66	
	18.3	18	–	Taylor et al. (2009a)
	12.6	29	–	
	10.5	34	–	
	24	19–39	57.7	Hunt and Cable (2020)
	14	60–75	63.7	
Argulus coregoni	18–22	121–426	73	Hakalahti et al. (2004)
	18–22	181–366 (when 2 days cold shock given at 1 °C)	81	
	18–22	121–302 (when 2 week cold shock given at 1 °C)	69	
Argulus siamensis	0	Nil	Nil	Sahoo et al. (2013a)
	4	20 (only when brought back to 28 °C within 3 days of incubation at 4 °C)	20	
	15	18 (only when brought back to 28 °C within 20 days of incubation at 15 °C)	30	
	28	15	75	
	32	10	60	
Argulus bengalensis	28	12–16	96.6	Banerjee et al. (2016)

35 °C but take about 61 days at 15 °C. The eggs of a closely related species, *A. foliaceus*, hatch in 17 days at 23 °C, but take 30 days at 20 °C (Steckler and Yanong 2012). Shafir and van As (1986) made a detailed study on the temperature-dependent development of eggs and hatching in *A. japonicus.* The first eggs developed and hatched after 61, 28, 17, 13, and 10 days, respectively, at 15, 20, 25, 30, and 35 °C. However, the time taken for egg development and hatching at different temperatures was non-synchronized among the eggs present in the strings. At 10 °C, except for color changes in the first 24 h, the egg did not develop further. The average hatching of these eggs was 18, 45, 55, 40, 28% at 15, 20, 25, 30, 35 °C, respectively, in the treatments, while the controls were 64% at 20 °C and 78% at 25 °C, which were significantly higher than the treatments. This implies that the optimal temperature range was between 20 and 30 °C for increased hatching, whereas hatching was substantially lower outside of this range.

Sahoo et al. (2013a) studied the impact of temperature on the development of *A. siamensis* eggs by incubating the eggs at different temperatures 0, 4, 15, 28, and 32 °C for 3–20 days and the time taken for the development of eggs and hatching into metanauplius larvae, revealing temperature has a significant impact. *A. siamensis* eggs incubated at 32 °C hatched out to metanaupliar larvae in 10 days, with a hatching percentage of 60; eggs incubated at 28 °C developed into larvae in 15 days, with a hatching percentage of 75. Eggs incubated at 15 °C did not develop. However, after being returned to the room temperature (25–28 °C), it took 18 days to develop into the metanauplii with a mere 30% hatching success. When eggs are stored at 4 °C for 3 days and returned to room temperature, they develop into the naupliar stage in 20 days with a 20% hatching rate. However, the eggs stored at 4 °C for an extended period of 3 days did not develop. Further, the eggs that were held at 0 °C did not develop. The time required for hatching decreases gradually as the incubation temperature rises, illustrating that development is temperature-dependent, with a temperature of 28 °C being the ideal condition.

Similarly, Hunt and Cable (2020) investigated the influence of temperature regimes on the hatching success of *A. foliaceus* eggs by incubating them at 24 and 14 °C. Eggs hatched after an average incubation period of 27 days (ranging from 19 to 39 days) at 24 °C and 67 days (ranging from 60 to 75 days) at 14 °C. Furthermore, the hatching rate varied between temperature treatments, ranging from 57.7% to 63.7%, with no significant difference between eggs incubated either at 24 or 14 °C. This demonstrates that *Argulus* is highly resistant to temperature variations, with even a 10 °C difference having no influence on hatching success. Egg development and hatching were substantially faster at 24 °C compared to 14 °C, implying that *A. foliaceus* would have a shorter generation time at higher temperatures because development and hatching occur more rapidly.

3.4 Effect on Off-Host Survival of Argulus

The activities and intensification of aquaculture practices have resulted in the increased movement of live fish in recent times, and there are substantial evidence that such movements, including the carrying water, have been responsible for the horizontal spread of *Argulus* and other pathogens from one farm to other. Water can be considered as a vector for these parasites, though the extent to which it can do so is determined by its off-host survival time. Walker et al. (2011b) explored the mean off-host survival times for different developmental stages of two argulid species, *A. japonicus* and *A. foliaceus*, at different temperature regimes and showed differences between developmental stages. The adult *A. japonicus* survived the longest duration of the host at 15 °C with a mean of 2.46–9.43 days (maximum 13 days) and for *A. foliaceus* at 9 °C; the maximum off-host survival time was 14 days. In general, the adult *A. foliaceus* survived at lower temperatures for a longer period of time than *A. japonicus*. Further, the larvae and juveniles of *A. japonicus* generally survived longer off-host than *A. foliaceus*. The maximum off-host survival durations for naupliar larvae of *A. japonicas* ranged from 3 to 9 days, while for *A. foliaceus* larvae it varied from 3 to 5 days. Juvenile lice exhibited a similar off-host survival pattern as naupliar larvae with maximal off-host survival times for *A. japonicus* and *A. foliaceus* were 5–12 days and 5–7 days, respectively. It was concluded that as lice mature, their off-host survival time rises. Further, Hunt and Cable (2020) examined the effect of temperature on/off-host survival of *A. foliaceus* metanauplii under different temperature scenarios. The off-host survival of metanauplii maintained at 24 °C was significantly lower than those maintained at 14 °C. Even on-host survival on sticklebacks at 14 °C fell significantly with time, with less than 50% survival after 21 days post-infection. It was also shown that metanauplii are highly resistant to sudden 10 °C temperature shock, with no impact on its survival. Hunt et al. (2021) also observed the *A. foliaceus* off-host activity followed a diurnal, circadian pattern with a distinct behavioral rhythm under light/dark conditions lost in total darkness. Sahoo et al. (2012) observed that the maximum off-host survival period of adult *A. japonicas* was 6 days and *A. siamensis* was 4 days; however, they did not correlate off-host survival with temperature.

3.5 Influence of *Argulus* Density on Host Species

Temperature has been shown to have a strong influence on the development rates of fish lice, with rising water temperatures likely to increase the infestation pressure on-farm and wild fish. Previous studies have shown that increased water temperature accelerates the prevalence and intensity of *Argulus* parasite infection, with male fish harboring significantly more parasites than females. However, the distribution of *Argulus* parasites on crucian carp and golden carp was found to be nearly equal in both male and female fish (Pasternak et al. 2000). Therefore, based on the above findings, it can be stated that parasite formation varies dramatically not only between fish species but also between fish genders (Kutlu and Ozturk 2006). Furthermore, Koyun (2011) investigates the effect of water temperature on *A. foliaceus* on different fish species and finds that increasing the temperature increases the load (density) of fish louse on fish, causing significant harm to the fish growth and health.

Estimating infection dynamics is critical for prevention and mitigation. Considering the influence of climate-driven changes on aquaculture, it is vital to have a comprehensive understanding of how parasites react in a variety of situations. It has been proven in the study of Hunt and Cable (2020) that temperature has a significant impact on parasite development, growth, and survival. The rate of egg hatching and development of *Argulus* parasites fasten at higher temperatures, but they live shorter lives when kept off the host fish. At higher temperatures, the parasites (*A. foliaceus*) are more likely to have a short generation time because their life cycle is completed faster than at lower or normal temperatures. The author also suggested that *A. foliaceus* grew faster on natural hosts with lower infection intensity at higher temperatures, whereas parasite growth was significantly slower when parasite density was high. The length of *A. foliaceus* increased with temperature and time; after 14 days, the length averaged 2.5, 1.9, and 1.1 mm at 24, 19, and 14 °C, respectively. On the one hand, fast life-history traits may enable argulids to exploit their hosts faster, but depending on host density, they may potentially limit infection. Furthermore, host species have an effect on parasite length (growth) over time; sticklebacks had larger *A. foliaceus* than guppies when infected with numerous parasites at an optimal density (Hunt and Cable 2020). Considering *A. foliaceus* averaged 0.618 mm in length at birth, reaching adulthood (4.7 mm) would take 45 days at 19 °C and 30 days at 24 °C for low infection in stickleback and guppies. However, for the higher infection density tests at 19 °C, *A. foliaceus* would take 50 days on sticklebacks and 55 days on guppies to reach adulthood (Hunt and Cable 2020).

3.6 Effect on Range Expansion and Seasonal Prevalence of Argulus

Argulus is a highly successful parasite due to its low host specificity, which allows it to infect a varied range of fish (including amphibian tadpoles) in its habitat, longer off-host survival times, high fecundity, and its direct life cycle, which has resulted in numerous cases of infection reaching the level of fatal epizootics (Holland and Kennedy 1997; Pasternak et al. 2000; Poly 2003; Harrison et al. 2006; Taylor et al. 2006; Walker et al. 2011a; Sahoo et al. 2012; Kumar et al. 2017; Kumari et al. 2018). Additionally, some *Argulus* species can tolerate temperatures ranging from 4 to 32 °C (Shafir and Oldewage 1992; Steckler and Yanong 2012; Sahoo et al. 2013a; Hunt and Cable 2020). These characteristics appear to be one of the primary reasons for the cosmopolitan distribution of many Argulus species. *A. japonicus* has been reported from all continents except for Antarctica (Poly 2008), frequently reported on goldfish and common carp; however, it has been reported to infect many other fish species. *A. siamensis* is found primarily on cultured carps in India, with *Labeo rohita* being the most susceptible and *Ctenopharyngodon idella* being the most resistant to this parasite (Sahoo et al. 2013a, b; Kar et al. 2016). *A. foliaceus* is found in cold temperate climates and infects a much wider range of fish hosts, including Cyprinidae, Salmonidae, Gobiidae, Gasterosteidae, Acipenseridae, frogs, and toads (Yamaguti 1963; Mikheev et al. 2007). *A. coregoni* had a pronounced preference for salmonid hosts, but it also infects cyprinids and other hosts and prefers cooler water than *A. foliaceus* (Hakalahti and Valtonen 2003; Mikheev et al. 2007). It was also explained that juvenile argulids of both species exhibited low host specificity, preferring to adhere to fish with higher body reflectivity. This suggests that such an intrinsic ontogenetic shift in host preference retains the majority of the parasite population on its primary host, ensuring successful reproduction under favorable conditions (Mikheev et al. 2007). Further, the seasonal prevalence of *Argulus* in Europe peaks during the late summer/early autumn and is relatively low during the winter (Walker et al. 2008). However, in the Indian subcontinent, the prevalence of *Argulus* in carp farms was recorded highest during the winter months and the summer month had the lowest parasitic prevalence (Sahoo et al. 2012; Chakraborty et al. 2020).

4 Effects of Changing Thermal Regimes on Hosts Infested with *Argulus*

4.1 Effect on Fish Immune Response

The temperature of water influences fish immune responses vary with the fish species; the degree of a temperature change and exposure duration. The first line of defense in fish is comprised of a diverse set of nonspecific immune mechanisms, which reacts quickly against all invading pathogens (Sahoo et al. 2021) and thus not reliant on prior recognition of the pathogen-associated molecular patterns (Tort et al. 2003). The innate defense strategy is usually effective enough to protect fish from invading pathogens until the acquired immune response gets in action (uses antigen-specific mechanisms) to target the pathogenic microbes. In fish, innate immunity has been proposed to replace specific immunity at a lower temperature (Magnadóttir et al. 1999; Abram et al. 2017). It has been revealed that an increase in temperature will stimulate the specific immune response and could result in increased serum immunoglobulin concentration and natural antibody titers (Alcorn et al. 2002).

Shameena et al. (2021) observed significantly decreased respiratory burst activity, myeloperoxidase, and lysozyme activity in goldfish co-infected with *Argulus* and *Aeromonas hydrophila* when exposed to 33 °C for 72 h than the control group while infected group exposed to 28 °C showed significantly higher values for NBT, MPO, and lysozyme activity. In addition, *Labeo rohita* infected with *A. siamensis* showed a reduced level of ceruloplasmin, serum α-2 macroglobulin activity, and alternative complement activity (Saurabh et al. 2010). Kar et al. (2015) assessed the immune responses of *Labeo rohita* infected with *A. siamensis* by quantifying the immune-relevant gene expression in the head kidney and skin and serum innate immune parameters during the infestation. Most of the skin-related genes were found to be significantly upregulated during infection, whereas TLR-22 and TNF-α were significantly downregulated initially, which afterward showed upregulation. However, most of the genes were found downregulated considerably in the head kidney, except IgM, and β-2 microglobulin genes were significantly upregulated at 3 days post-infection. The innate immune parameters, especially the serum complement activity and ceruloplasmin levels, were significantly lower in *Argulus* infected fish. Saurabh et al. (2011) also found upregulated TNF-α and TLR22 genes in the skin tissue of fish heavily infested *with Argulus*. It was believed that *A. siamensis* significantly modulates the immune response of rohu by downregulating various immune factors, which could be the probable reason why rohu is highly susceptible to *A. siamensis* parasitism. Parida et al. (2018) exclusively characterized the mucosal immune responses of rohu infested with *A. siamensis*. The author observed significantly upregulated expression of interleukins IL 6, IL 15, and IL 1β in the epidermal mucus of fish infected with the parasite. The upregulation of the IL1β gene and other pro-inflammatory cytokines during inflammatory responses could be due to the influx of macrophages to the site of inflammation (Esteban 2012). Das et al. (2015) found the increased expression of IL 15 gene in the head kidney and skin of *A. siamensis* infected rohu and hypothesized the possible role of this gene as an anti-inflammatory (both local and systemic) in parasitic host defense in fish. These results implicate that IL 15 might play a key role in regulating infection-induced inflammation at the mucus-associated site.

Furthermore, the major pro-inflammatory cytokine, such as IL 6, was found gradually upregulated in the mucus of infected rohu throughout the infection period (Parida et al. 2018). The cytokine IL 6 could stimulate the production of acute-phase proteins, which are responsible for mediating physiological responses in the host during injury or infection with infectious agents (Alvarez-Pellitero 2008). Ruane et al. (1999) studied the effects of *A. foliaceus* infestation on the immune response of rainbow trout in two parasitized groups, one of which had received cortisol feeding prior to infection. The study revealed that the stressor-induced immunomodulation was more distinct in parasitized fish after confinement, as evidenced by decreased alternative complement activity, lysozyme activity, and reduced oxygen radical production either immediately or 48 h after confinement. The number of circulating lymphocytes was significantly lower in the control and normal-fed group of infested fish. The findings suggest that a low level of ectoparasitic infestations causes stress for a prolonged period, with consequences that might impair response to subsequent stressors.

4.2 *Argulus*-Avoidance Strategies in Fish

The ability of hosts to detect the risk of infection is a critical requirement for parasite avoidance. Detection can occur before or after a parasite encounter as a result of specific parasite-associated signals, their contact, or establishment, which can trigger an avoidance mechanism(s) in the host (Wisenden et al. 2009). In the estuarine tidal pools of Canada, Poulin and FitzGerald (1988) looked at daily fluctuations in the extent of *A. canadensis* infection in three-spined and black-spotted sticklebacks. Both of these fish species harbored twice as many parasites during afternoons (when water temperatures were higher and fish moved closer to the bottom) as they did in mornings (when water temperatures were lower and fish swam closer to the surface).

The authors also confirmed that the success of parasite attacks was unaffected by water temperature. Therefore, their findings suggest that the observed temporal patterns of infection are attributable to diurnal changes in stickleback distribution driven by daily variations in water temperature and oxygen tensions.

Further, in their subsequent study, Poulin and Fitzgerald (1989) demonstrated the importance of substrate and vegetation in determining the infection levels and observed that sticklebacks might change their habitat preferences to avoid parasites when freed from the tide pool environmental regime. Sticklebacks showed a preference towards vegetated benthic habitats when *Argulus* sp. were absent but moved to the surface when parasites were introduced; also, the fishes showed reduced preference for vegetation. Dugatkin et al. (1994) observed Juvenile three-spined sticklebacks were avoiding shoals of conspecifics infected with *Argulus canadensis* to some extent because the infected individuals exhibited abnormal behavior. Another possible reason for parasite evading might be the larger size of the parasites, which are visible to hosts; however, in the case of *Argulus* sp., parasites alone could not provoke avoidance behavior.

5 *Argulus* Parasitism and Co-infection in Changing Thermal Regimes

The shift in temperature represents a complex amalgamation of stressors, though; synergies with other abiotic stressors could exacerbate the negative impacts on the aquatic creatures (Woodward et al. 2010). Many studies report that the parasitic infections being a primary pathogen increases the risk of secondary infection with bacterial or fungus and may act as a vector to transmit bacterial or viral pathogens (Yildiz and Kumantas 2002; Kotob et al. 2017). It is shown in numerous studies that co-infections significantly enhance the severity of some infectious diseases, particularly bacterial diseases (Busch et al. 2003) and their synergistic effect shows higher mortalities in parasitized/bacterial co-infected fish interactions (Lhorente et al. 2014; Zhang et al. 2015; Shameena et al. 2021). The parasite like *Argulus* recurrently penetrates the fish skin for blood-feeding, causing injuries that eventually transform into ulcers and serving as a portal for secondary invaders like *Aeromonas* or *Pseudomonas*, culminating in severe skin ulceration (Noaman et al. 2010). In a recent study, higher temperatures (33 °C) were proven to increase the intensity of Argulus infestation in goldfish more than lower temperatures (23 and 20 °C, respectively), indicating that infection increases in a temperature-dependent manner (Shameena et al. 2021). Remarkably, the infections become more detrimental to hosts as temperature rises, resulting in high mortality in the co-infected group (with *Aeromonas hydrophila* and *Argulus)* of fish. This might be due to the increased virulence and pathogenicity of bacteria and parasites at elevated temperatures. Several studies have suggested the enhanced multiplication rate of bacteria and parasites at increasing temperatures will impose a direct effect on the degree and nature of pathology experienced by hosts (Zhang et al. 2015; Bandilla et al. 2006;

Callaway et al. 2012) can be directly correlated with the consequences of global warming on fish diseases.

6 Conclusion

With the predicted climate change scenario over the twenty-first century, both the average temperature and the frequency and intensity of extreme temperature events are expected to rise. Predicting the influence of these events on parasitism of *Argulus* in lentic habitats would be particularly challenging because temperature alters the biology of hosts, parasites, and their interactions in a variety of ways. Furthermore, temperature changes should not be viewed in isolation because other changes in the environment may also have a synergistic, additive, or antagonistic effect. Nonetheless, experiments with amenable host-parasite systems can provide insight into the types of repercussions that could occur. One of the most likely consequences of an altered thermal scenario is a shift in the spatiotemporal distribution of *Argulus* due to their fastened life-history traits, which may increase host susceptibility to other groups of pathogens and cumulative mortality among cultured fish.

References

Abram QH, Dixon B, Katzenback BA (2017) Impacts of low temperature on the teleost immune system. Biology 6(4):39

Ahne W, Bjorklund HV, Essbauer S, Fijan N, Kurath G, Winton JR (2002) Spring viremia of carp (SVC). Dis Aquat Org 52(3):261–272

Alcorn SW, Murray AL, Pascho RJ (2002) Effects of rearing temperature on immune functions in sockeye salmon (Oncorhynchus nerka). Fish Shellfish Immunol 12(4):303–334

Alfonso S, Gesto M, Sadoul B (2021) Temperature increase and its effects on fish stress physiology in the context of global warming. J Fish Biol 98(6):1496–1508. https://doi.org/10.1111/jfb.14599

Altizer S, Ostfeld RS, Johnson PTJ, Kutz S, Harvell CD (2013) Climate change and infectious diseases: from evidence to a predictive framework. Science 341:514–519. https://doi.org/10.1126/science.1239401

Alvarez-Pellitero P (2008) Fish immunity and parasite infections: from innate immunity to immunoprophylactic prospects. Vet Immunol Immunopathol 126(3–4):171–198

Andersen PS, Buchmann K (1998) Temperature dependent population growth of *Gyrodactylus derjavini* on rainbow trout, *Oncorhynchus mykiss*. J Helminthol 72(1):9–14. https://doi.org/10.1017/S0022149X00000900

Avenant-Oldewage A (2001) *Argulus japonicus* in the Olifants River system-possible conservation threat? South Afr J Wildlife Res 31(1):59–63

Avenant-Oldewage A, Lutsch E (1995) The ultrastructure of the newly hatched *Argulus japonicus* Thiele, 1900 larvae (Branchiura). Crustaceana 68(3):329–340

Bandilla M, Hakalahti T, Hudson PJ, Valtonen ET (2005) Aggregation of *Argulus coregoni* (Crustacea: Branchiura) on rainbow trout (*Oncorhynchus mykiss*): a consequence of host susceptibility or exposure? Parasitology 130(2):169–176

Bandilla M, Valtonen ET, Suomalainen LR, Aphalo PJ, Hakalahti T (2006) A link between ectoparasite infection and susceptibility to bacterial disease in rainbow trout. Int J Parasitol 36(9):987–991

Banerjee A, Poddar S, Manna S, Saha SK (2016) Mutualistic association of rotifer Philodina roseola with the branchiuran fish ectoparasite *Argulus bengalensis* at its embryonic stage. Biol Lett 12 (3):20151043. https://doi.org/10.1098/rsbl.2015.1043

Barber I, Arnott SA, Braithwaite VA, Andrew J, Huntingford FA (2001) Indirect fitness consequences of mate choice in sticklebacks: offspring of brighter males grow slowly but resist parasitic infections. Proc R Soc B Biol Sci 268(1462):71–76. https://doi.org/10.1098/rspb.2000.1331

Bauer ON, Musselius VA, Strelkov YA (1973) Disease of pond fishes. Israel Program for Scientific Translations, Ltd., Jerusalem. 220 pp

Brunner FS, Eizaguirre C (2016) Can environmental change affect host/parasite-mediated speciation? Zoology 119(4):384–394. https://doi.org/10.1016/j.zool.2016.04.001

Busch S, Dalsgaard I, Buchmann K (2003) Concomitant exposure of rainbow trout fry to *Gyrodactylus derjavini* and *Flavobacterium psychrophilum*: effects on infection and mortality of host. Vet Parasitol 117(1–2):117–122

Byers JE (2021) Marine parasites and disease in the era of global climate change. Annu Rev Mar Sci 13:397–420

Callaway R, Shinn AP, Grenfell SE, Bron JE, Burnell G, Cook EJ, Crumlish M, Culloty S, Davidson K, Ellis RP, Flynn KJ (2012) Review of climate change impacts on marine aquaculture in the UK and Ireland. Aquat Conserv Mar Freshwat Ecosyst 22(3):389–421

Chakraborty R, Mukherjee D, Bardhan A, Mali P, Sanyal KB, Dash G (2020) Prevalence of Argulus sp. in Indian major carps from Bhangore block of south 24 Parganas District, West Bengal, India. J Fish Sci 2(1):5–8

Cohen JM, Civitello DJ, Venesky MD, McMahon TA, Rohr JR (2019) An interaction between climate change and infectious disease drove widespread amphibian declines. Glob Chang Biol 25(3):927–937. https://doi.org/10.1111/gcb.14489

Costello MJ (2009) The global economic cost of sea lice to the salmonid farming industry. J Fish Dis 32(1):115–118. https://doi.org/10.1111/j.1365-2761.2008.01011.x

Crossan J, Paterson S, Fenton A (2007) Host availability and the evolution of parasite life-history strategies. Evolution 61(3):675–684

Das S, Mohapatra A, Kar B, Sahoo PK (2015) Molecular characterization of interleukin 15 mRNA from rohu, Labeo rohita (Hamilton): its prominent role during parasitic infection as indicated from infection studies. Fish Shellfish Immunol 43(1):25–35

Dugatkin LA, FitzGerald GJ, Lavoie J (1994) Juvenile three-spined sticklebacks avoid parasitized conspecifics. Environ Biol Fish 39(2):215–218

Esteban MA (2012) An overview of the immunological defenses in fish skin. ISRN Immunol 2012: 1. https://doi.org/10.5402/2012/853470

Granada L, Sousa N, Lopes S, Lemos MFL (2016) Is integrated multitrophic aquaculture the solution to the sectors' major challenges?—A review. Rev Aquacult 8(3):283–300. https://doi.org/10.1111/raq.12093

Gresty KA, Boxshall GA, Nagasawa K (1993) The fine structure and function of the cephalic appendages of the branchiuran parasite, *Argulus japonicus* Thiele. Philos Trans R Soc Lond B Biol Sci 339(1287):119–135

Groner ML, Gettinby G, Stormoen M, Revie CW, Cox R (2014) Modelling the impact of temperature-induced life history plasticity and mate limitation on the epidemic potential of a marine ectoparasite. PLoS One 9:e88465

Hadfield KA, Smit NJ (2019) Parasitic crustacea as vectors. In: Parasitic Crustacea. Springer, Cham, pp 331–342

Hakalahti T, Valtonen ET (2003) Population structure and recruitment of the ectoparasite *Argulus coregoni* Thorell (Crustacea: Branchiura) on a fish farm. Parasitology 127(1):79–85

Hakalahti T, Pasternak AF, Valtonen ET (2004) Seasonal dynamics of egg laying and egg-laying strategy of the ectoparasite Argulus coregoni (Crustacea: Branchiura). Parasitology 128(6): 655–660. https://doi.org/10.1017/S0031182004004986

Hakalahti T, Karvonen A, Valtonen ET (2006) Climate warming and disease risks in temperate regions - *Argulus coregoni* and *Diplostomum spathaceum* as case studies. J Helminthol 80(2): 93–98. https://doi.org/10.1079/JOH2006351P

Hakalahti T, Mikheev VN, Valtonen ET (2008) Control of freshwater fish louse *Argulus coregoni*: a step towards an integrated management strategy. Dis Aquat Org 82(1):67–77. https://doi.org/10.3354/dao01971

Harrison A, Gault N, Dick J (2006) Seasonal and vertical patterns of egg-laying by the freshwater fish louse *Argulus foliaceus* (Crustacea: Branchiura). Dis Aquat Org 68:167–429. https://doi.org/10.3354/dao068167

Hogans B (1994) 3.2.15 Branchiuran fish louse disease. https://units.fisheries.org/fhs/wp-content/uploads/sites/30/2017/08/3.2.15-Branchiuran-2014.pdf

Holland CV, Kennedy CR (1997) A checklist of parasitic helminth and crustacean species recorded in freshwater fish from Ireland. In: Biology and environment: proceedings of the Royal Irish Academy. Royal Irish Academy, Dublin, pp 225–243

Hunt R, Cable J (2020) Life in the fast lane: temperature, density and host species impact survival and growth of the fish ectoparasite *Argulus foliaceus*. J Therm Biol 92:102687. https://doi.org/10.1016/j.jtherbio.2020.102687

Hunt R, Cable J, Ellison A (2021) Shining a light on parasite behaviour: daily patterns of Argulus fish lice. Parasitology 148(7):850–856

IPCC (2015) In: Pachauri RK, Allen MR, Barros VR, Broome J, Cramer W, Christ R, Church JA, Clarke L, Dahe Q, Dasgupta P, Dubash NK (eds) IPCC climate change 2014: synthesis report. IPCC, Geneva, p 151

Kar B, Mohanty J, Hemaprasanth KP, Sahoo PK (2015) The immune response in rohu, Labeo rohita (Actinopterygii: Cyprinidae) to Argulus siamensis (Branchiura: Argulidae) infection: kinetics of immune gene expression and innate immune response. Aquac Res 46(6):1292–1308

Kar B, Moussa C, Mohapatra A, Mohanty J, Jayasankar P, Sahoo PK (2016) Variation in susceptibility pattern of fish to Argulus siamensis: do immune responses of host play a role? Vet Parasitol 221:76–83

Kar B, Mohapatra A, Mohanty J, Sahoo PK (2017) Evaluation of ribosomal P0 peptide as a vaccine candidate against *Argulus siamensis* in *Labeo rohita*. Open Life Sci 12(1):99–108

Karvonen A, Rintamaki P, Jokela J, Valtonen ET (2010) Increasing water temperature and disease risks in aquatic systems: climate change increases the risk of some, but not all, diseases. Int J Parasitol 40:1483–1488

Kotob MH, Menanteau-Ledouble S, Kumar G, Abdelzaher M, El-Matbouli M (2017) The impact of co-infections on fish: a review. Vet Res 47(1):1–12

Koyun M (2011) The effect of water temperature on Argulus foliaceus L. 1758 (Crustacea; Branchiura) on different fish species. Notulae Scientia Biologicae 3(2):16–19

Kumar S, Raman RP, Kumar K, Pandey PK, Kumar N, Mohanty S, Kumar A (2012) In vitro and in vivo antiparasitic activity of Azadirachtin against Argulus spp. in *Carassius auratus* (Linn. 1758). Parasitol Res 110(5):1795–1800

Kumar S, Sathish Kumar T, Vidya R, Pandey PK (2017) A prospective of epidemiological intervention in investigation and management of argulosis in aquaculture. Aquac Int 25(1): 303–325

Kumari P, Ramesh M, Shameena SS, Raman RP, Kumar S (2018) Argulosis: threat for ornamental fish industry. Aquaculture Times, pp 7–11

Kumari P, Kumar S, Ramesh M, Shameena S, Deo AD, Rajendran KV, Raman RP (2019) Antiparasitic effect of aqueous and organic solvent extracts of *Azadirachta indica* leaf against *Argulus japonicus* in *Carassius auratus*. Aquaculture 511:634175

Kutlu HL, Ozturk MO (2006) Metazoan parasites of *Cyprinus carpio* from Lake Karamik (Afyonkarahisar) on anatomical, morphological and ecological research. J Fish 23(3–4): 389–393

Lafferty KD, Shaw JC (2013) Comparing mechanisms of host manipulation across host and parasite taxa. J Exp Biol 216:56–66. https://doi.org/10.1242/jeb.073668

Lewin WC, Arlinghaus R, Mehner T (2006) Documented and potential biological impacts of recreational fishing: insights for management and conservation. Rev Fish Sci 14:305–367. https://doi.org/10.1080/10641260600886455

Lhorente JP, Gallardo JA, Villanueva B, Carabaño MJ, Neira R (2014) Disease resistance in Atlantic salmon (Salmo salar): coinfection of the intracellular bacterial pathogen Piscirickettsia salmonis and the sea louse Caligus rogercresseyi. PLoS One 9(4):e95397

Lõhmus M, Björklund M (2015) Climate change: what will it do to fish—parasite interactions? Biol J Linn Soc 116(2):397–411

Magnadóttir B, Jónsdóttir H, Helgason S, Björnsson B, Jørgensen TØ, Pilström L (1999) Humoral immune parameters in Atlantic cod (Gadus morhua L.): I. the effects of environmental temperature. Comp Biochem Physiol B: Biochem Mol Biol 122(2):173–180

Marcogliese DJ (2001) Implications of climate change for parasitism of animals in the aquatic environment. Can J Zool 79(8):1331–1352

Masson-Delmotte V, Zhai P, Pörtner HO, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S (2018) Global warming of 1.5°C. An IPCC special report. Cambridge University Press, Cambridge

Mikheev VN, Pasternak AF, Valtonen ET (2007) Host specificity of Argulus coregoni (Crustacea: Branchiura) increases at maturation. Parasitology 134(12):1767–1774

Mikheev VN, Pasternak AF, Valtonen ET (2015) Behavioural adaptations of argulid parasites (Crustacea: Branchiura) to major challenges in their life cycle. Parasit Vectors 8(1):1–10

Morley NJ, Lewis JW (2014) Temperature stress and parasitism of endothermic hosts under climate change. Trends Parasitol 30:221–227. https://doi.org/10.1016/j.pt.2014.01.007

Ngoan LD (2018) Effects of climate change in aquaculture: case study in Thua Thien Hue Province, Vietnam. Biomed J Sci Tech Res 10:2018. https://doi.org/10.26717/BJSTR.2018.10.001892

Noaman V, Chelongar Y, Shahmoradi AH (2010) The first record of Argulus foliacesus (Crustacea: Branchiura) infestation on lionhead goldfish (Carassius auratus) in Iran. Iran J Parasitol 5(2):71

Parida S, Mohapatra A, Kar B, Mohanty J, Sahoo PK (2018) Transcriptional analysis of immune-relevant genes in the mucus of Labeo rohita, experimentally infected with Argulus siamensis. Acta Parasitol 63(1):125–133

Pasternak AF, Mikheev VN, Valtonen ET (2000) Life history characteristics of Argulus foliaceus L. (Crustacea: Branchiura) populations in Central Finland. In: Annales Zoologici Fennici. Finnish Zoological and Botanical Publishing Board, Basel, pp 25–35

Paull SH, Johnson PT (2011) High temperature enhances host pathology in a snail–trematode system: possible consequences of climate change for the emergence of disease. Freshw Biol 56(4):767–778

Poly WJ (2003) Argulus ambystoma, a new species parasitic on the salamander Ambystoma dumerilii from Mexico (Crustacea: Branchiura: Argulidae). Ohio J Sci 103:52–61

Poly WJ (2008) Global diversity of fishlice (Crustacea: Branchiura: Argulidae) in freshwater. Hydrobiologia 595(1):209–212

Poulin R (2020) Meta-analysis of seasonal dynamics of parasite infections in aquatic ecosystems. Int J Parasitol 50(6–7):501–510. https://doi.org/10.1016/j.ijpara.2020.03.006

Poulin R, FitzGerald GJ (1988) Water temperature, vertical distribution, and risk of ectoparasitism in juvenile sticklebacks. Can J Zool 66(9):2002–2005

Poulin R, FitzGerald GJ (1989) A possible explanation for the aggregated distribution of Argulus canadensis Wilson, 1916 (Crustacea: Branchiura) on juvenile sticklebacks (Gasterosteidae). J Parasitol 75:58–60

Rahman MM (1995) Some aspects of the biology of a freshwater fish parasite *Argulus foliaceus* (L.) (Argulidae, Branchiura, Crustacea). Bangladesh J Zool 23(1):77–86

Reid GK, Gurney-Smith HJ, Flaherty M, Garber AF, Forster I, Brewer-Dalton K, Knowler D, Marcogliese DJ, Chopin T, Moccia RD, Smith CT (2019) Climate change and aquaculture: considering adaptation potential. Aquac Environ Interact 11:603–624. https://doi.org/10.3354/AEI00333

Ruane NM, Nolan DT, Rotllant J, Tort L, Balm PHM, Wendelaar Bonga SE (1999) Modulation of the response of rainbow trout (Oncorhynchus mykiss Walbaum) to confinement, by an ectoparasitic (Argulus foliaceus L.) infestation and cortisol feeding. Fish Physiol Biochem 20(1):43–51

Rushton-Mellor SK, Boxshall GA (1994) The developmental sequence of *Argulus foliaceus* (Crustacea: Branchiura). J Nat Hist 28(4):763–785

Sahoo PK, Hemaprasanth K, B., Garnayak, S.K. and Mohanty, J. (2012) Mixed infection of Argulus japonicus and Argulus siamensis (Branchiura, Argulidae) in carps (Pisces, Cyprinidae): loss estimation and a comparative invasive pattern study. Crustaceana 85(12–13):1449–1462

Sahoo PK, Mohanty J, Kar B, Mohanty BR, Garnayak SK, Jena JK (2013a) Egg laying strategies and effect of temperature on egg development of Argulus siamensis. J Parasit Dis 37(2):158–162. https://doi.org/10.1007/s12639-012-0148-6

Sahoo PK, Mohanty J, Garnayak SK, Mohanty BR, Kar B, Prasanth H, Jena JK (2013b) Estimation of loss due to argulosis in carp culture ponds in India. Indian J Fish 60(2):99–102

Sahoo PK, Mishra M, Mohapatra A, Parida S, Mohanty J (2021) Vaccination approach to prevent Argulus siamensis infection-success, challenges and preparedness. Fish Shellfish Immunol Rep 2:100023

Saurabh S, Sahoo PK (2010) Non-specific immune responses of the Indian major carp Labeo rohita (Hamilton) to infestation by the freshwater fish louse Argulus siamensis (Wilson). Indian J Fish 57:45–53

Saurabh S, Sahoo PK, Mohanty BR, Mohanty J, Jena JK, Mukherjee SC, Sarangi N (2010) Modulation of the innate immune response of rohu *Labeo rohita* (Hamilton) by experimental freshwater lice *Argulus siamensis* (Wilson) infection. Aquac Res 41(9):e326–e335

Saurabh S, Mohanty BR, Sahoo PK (2011) Expression of immune-related genes in rohu Labeo rohita (Hamilton) by experimental freshwater lice Argulus siamensis (Wilson) infection. Vet Parasitol 175(1–2):119–128

Shafir A, Oldewage WH (1992) Dynamics of a fish ectoparasite population: opportunistic parasitism in Argulus japonicus (Branchiura). Crustaceana 62:50–64

Shafir A, Van As JV (1986) Laying, development and hatching of eggs of the fish ectoparasite *Argulus japonicus* (Crustacea: Branchiura). J Zool 210(3):401–413

Shahjahan MD, Kitahashi T, Ando H (2017) Temperature affects sexual maturation through the control of kisspeptin, kisspeptin receptor, GnRH and GTH subunit gene expression in the grass puffer during the spawning season. Gen Comp Endocrinol 243:138–145

Shameena SS, Kumar S, Kumar K, Raman RP (2021) Role of temperature and co-infection in mediating the immune response of goldfish. Microb Pathog 156:104896

Shimura S (1983) Seasonal occurrence, sex ratio and site preference of Argulus coregoni Thorell (Crustacea: Branchiura) parasitic on cultured freshwater salmonids in Japan. Parasitology 86(3): 537–552. https://doi.org/10.1017/S0031182000050721

Soleng A, Jansen P, Bakke T (1998) Transmission of the monogenean *Gyrodactylus salaris*. Parasitol Int 47:319. https://doi.org/10.1016/S1383-5769(98)80927-6

Steckler N, Yanong RP (2012) Argulus (fish louse) infections in fish. Fisheries and Aquatic Sciences Publications, University of Florida, Florida, pp 1–4

Stensgaard A-S, Vounatsou P, Sengupta ME, Utzinger J (2019) Schistosomes, snails and climate change: current trends and future expectations. Acta Trop 190:257–268. https://doi.org/10.1016/j.actatropica.2018.09.013

Taylor NGH, Sommerville C, Wootten R (2006) The epidemiology of Argulus spp. (Crustacea: Branchiura) infections in stillwater trout fisheries. J Fish Dis 29(4):193–200

Taylor NGH, Wootten R, Sommerville C (2009a) The influence of risk factors on the abundance, egg laying habits and impact of Argulus foliaceus in stillwater trout fisheries. J Fish Dis 32(6): 509–519. https://doi.org/10.1111/j.1365-2761.2009.01007.x

Taylor NGH, Wootten R, Sommerville C (2009b) Using length-frequency data to elucidate the population dynamics of Argulus foliaceus (Crustacea: Branchiura). Parasitology 136(9): 1023–1032. https://doi.org/10.1017/S0031182009006520

Tinsley RC, York JE, Everard AL, Stott LC, Chapple SJ, Tinsley MC (2011) Environmental constraints influencing survival of an African parasite in a north temperate habitat: effects of temperature on egg development. Parasitology 138(8):1029–1038. https://doi.org/10.1017/S0031182011000461

Tort L, Balasch JC, Mackenzie S (2003) Fish immune system. A cross roads between innate and adaptive responses. Imunología 3:277–286

van Dijk J, Morgan ER (2008) The influence of temperature on the development, hatching and survival of Nematodirus battus larvae. Parasitology 135(2):269–283. https://doi.org/10.1017/S0031182007003812

Walker PD (2008) Argulus-the ecology of a fish pest. Thesis. Radboud University, Nijmegen

Walker PD, Flik G, Bonga SEW (2004) The biology of parasites from the genus Argulus and a review of the interactions with its host. In: Wiegertjes GF, Flik G (eds) Host-parasite interactions. Taylor & Francis, London, pp 107–128

Walker PD, Harris JE, Velde GVD, Wendelaar Bonga SE (2008) Differential host utilisation by different life history stages of the fish ectoparasite Argulus foliaceus (Crustacea: Branchiura). Folia Parasitol 55:141–149

Walker PD, Russon IJ, Haond C, Van Der Velde G, Wendelaar-Bonga SE (2011a) Feeding in adult Argulus japonicus Thiele, 1900 (Maxillopoda, Branchiura), an ectoparasite on fish. Crustaceana 84:307–318

Walker PD, Russon IJ, Duijf R, Der Velde GV, Bonga SW (2011b) The off-host survival and viability of a native and non-native fish louse (Argulus, Crustacea: Branchiura). Curr Zool 57(6):828–835

Wedemeyer GA (1997) Effects of rearing conditions on the health and physiological quality of fish in intensive culture. In: Iwama GK, Pickering AD, Sumpter JP, Schreck CB (eds) Fish stress and health in aquaculture. Cambridge University Press, Cambridge, pp 35–72

Wisenden BD, Rugg ML, Korpi NL, Fuselier LC (2009) Lab and field estimates of active time of chemical alarm cues of a cyprinid fish and an amphipod crustacean. Behaviour 146:1423–1442

Woodward G, Perkins DM, Brown LE (2010) Climate change and freshwater ecosystems: impacts across multiple levels of organization. Philos Trans R Soc B Biol Sci 365(1549):2093–2106

Yamaguti S (1963) Parasitic Copepoda and Branchiura of fishes. Interscience Publications, New York. 1103 pp

Yildiz K, Kumantas A (2002) Argulus foliaceus infection in a goldfish (*Carassius auratus*). Israel J Vet Med 57(3):118–120

Zhang C, Li DL, Chi C, Ling F, Wang GX (2015) Dactylogyrus intermedius parasitism enhances Flavobacterium columnare invasion and alters immune-related gene expression in Carassius auratus. Dis Aquat Org 116(1):11–21

Effect of Environmental Variability on the Pigmentation of Fishes

Sarvendra Kumar, Showkat Ahmad Dar, and Susmita Rani

Abstract

A wide range of functions in animal species depends on the pattern of color. The pigmentation pattern in fish depends on the spatial combination and number of chromatophore types. Color in the animal also depends on the species. During life, color can change, and the changes are a response to abiotic and biotic environmental factors. Nutritional quality, UV light incidence, the intensity of light, and social interactions also change the pigmentation pattern in fishes. Quality criteria decide the market value of ornamental fish species, and culture species for fish is the pigmentation system of the skin. The external signal infers its condition of culture and its welfare. The pattern of pigmentation defects is a significant cause of loss in aquaculture production. In the case of fish exhibiting diverse pigmentation patterns, the pigmentation pattern depends on the stage of development. Despite the use of various methodologies to enhance the production of freshwater and marine water species, pigment abnormalities are still being reported at higher rates in larvae. The reason for pigmentation abnormalities is unknown; the most probable cause for the color abnormalities is the interaction between genetic and environmental factors.

Keywords

Pigmentation · Chromatophores · Photoreceptor · Melanin · α-MSH

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1 Introduction

Aquaculture now plays a critical role in revenue generation, food and nutrition security, and preserving local biodiversity and cultural traditions, particularly in undeveloped countries (Belton et al. 2018). Several types of chromatophore and their number and spatial arrangement determine the pattern of skin pigmentation, which is species-specific. This trait can change throughout time, as for as during the reproduction cycle or in response to abiotic and biotic environmental factors (nutrition and social interactions). Because it functions as an external signal to understand its well-being and the culture conditions utilized, the most crucial factor for quality criteria for fish species is fish skin pigmentation, speaking to the market value, which further depicts the requirements of quality dictating the market value of fish for consumption for human and decorative use (Harpaz and Padowicz 2007). Pigmentation pattern failings are the most common causes of loss of aquaculture production. Patterns of color in animals, mainly fish, are involved in various tasks. Several studies have shown to learn more about the mechanisms that underpin fish pigmentation and the impact that rearing settings have on it.

2 Pigmentation/Coloration in Fishes

Color consists of two types of pigments: structural and pigmentary. Light and tissue nanostructure interaction produces structural color (Parker and Martini 2006; Roberts et al. 2012). Reflection of light in iridophores (fish, reptiles, and amphibians) (Kawaguti 1965; Rudh and Qvarnström 2013; Olsson et al. 2013), scattering of light in bird barbules (Roulin and Ducrest 2013), or diffraction gratings in antenna hairs of crustaceans are all responsible for structural hues (Parker and Martini 2006). Chemical pigments deposited in specialized chromatosomes within pigment cells (chromatophores) produce pigmentary shades (Prum 2006; Roulin and Ducrest 2013). Because pigment cells are spread in layers in integument structures, pigmentary colors are usually associated with structural colors.

Two different pigmentation patterns determine the coloration of an adult fish. In adult Zebra fish, two separate pigment-patterning mechanisms contribute to the coloration of fish, i.e., an ancient mechanism behind dorsal-ventral patterning involving the expression of dorsal-ventral differential asip1 gene and a newer striping based on the mechanism of cell-cell interaction (Ceinos et al. 2015). But these genetically shaped mechanisms of pigment-patterning can be altered to some extent in response to various environmental factors and characterize the most captivating features of pigmentation in fish. Additionally, during the state of development, fish can show multiple patterns of pigmentation. But the phenotype color of the larva is different from its adult phenotype (Parichy et al. 2011). The standard color of body pattern in larvae of fish occasionally results in faulty pigmentation in adults. Several pigmentary flaws may arise during the metamorphosis of larvae, from the phenotype of larvae to the phenotype of adults (Bolker and Hill 2000; Ceinos et al. 2015). All organisms have modified their behavior and purposes in response to variation in the external indicators. An indicator such as the light-dark and 24 h LD cycles is the most prominent. Still, other factors such as water salinity, temperature or rainfall, and food availability can also affect rhythms. Several functions are observed in daily rhythms like shoaling behavior, food intake, thermoregulation, skin pigmentation, and oxygen consumption during larval development (Ekström and Meissl 1997).

In fish, larval development, sedation, locomotory behavior, oxygen consumption, skin pigmentation, feed consumption, thermoregulation, and behavior shoaling are among several functions that show daily rhythms (Ekström and Meissl 1997).

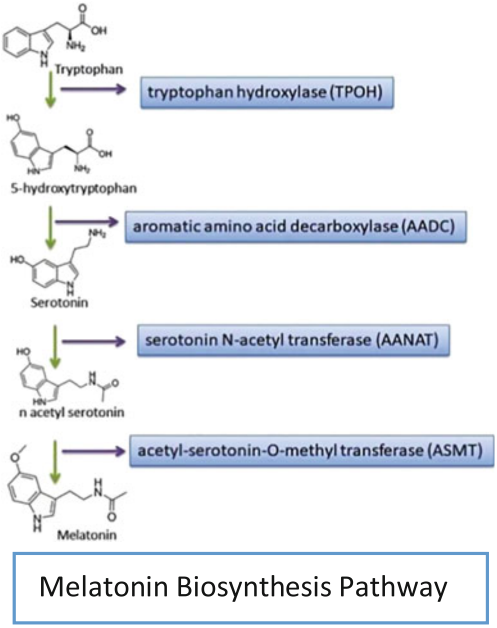
3 Sources of Melatonin Production

The pineal photoreceptors are structurally analogies to the retinal cones (Ekström and Meissl 1997). They are highly light-sensitive, with similar composition in lipids and proteins of the phototransduction cascade. Excitatory neurotransmitters (aspartate or glutamate) is inhibited by cell hyperpolarisation in response to light stimuli. The excitatory neurotransmitter grasps the ganglion cell directly to the pineal organ. Those signals are reflected by the response's photoreceptor cells, which is a luminance detector that delivers information on the light intensity, day duration time, and spectral content. It is essential to know that the retinal ganglion cells and pineal gland may target comparable brain areas, mainly in the thalamus and pretectum (Ekström and Meissl 1997). In addition to the excitatory neurotransmitter, the pineal and retinal photoreceptors produce melatonin at night by cell depolarization (Falcon 1999).

4 Mechanism of Melanin Production

Pineal cells take tryptophan for the synthesis of melatonin. Two enzymatic steps permit the arrangement of serotonin from tryptophan: tryptophan hydroxylation allows the incorporation of hydroxytryptophan, which is decarboxylated by the aromatic amino corrosive decarboxylase, driving the structure of serotonin.

Another two enzymatic step transformations of serotonin to melatonin are as follows: formation of *N*-acetylserotonin by the catalysis of arylalkylamine *N*-acetyltransferase (AANAT), and the hydroxy indole-*O*-methyltransferase (HIOMT) converts the *N*-acetyl serotonin into melatonin (Falcón et al. 2007). During the daytime, the level of serotonin is high and low at night, and melatonin is a shift pattern with an elevated pattern day and night (Falcon 1999; Bromage et al. 2001). The rise in melatonin production at nighttime by the pineal reflects an increase in the activity of arylalkylamine *N*-acetyltransferase. In contrast, hydroxy indole-*O*-methyltransferase activity remains relatively steady throughout the LD cycle.



5 Role of Temperature on Melatonin Biosynthesis

Since fish are ectotherms, their body temperature is directly affected by the peripheral temperature, which varies on a seasonal and daily basis. Various studies have shown that the temperature modulates melatonin secretion directly by regulating AANAT2 in the pineal organ (Benyassi et al. 2001). Remarkably, (a) there is a good correlation between the fish's optimum physiological temperature and the peak of responses of AANAT2 (Oncorhynchus mykiss at 12 °C, Esox Lucius at 20 °C, Sparus aurata at 27 °C); (b) the enzyme response towards the temperature is its intrinsic property as similar response curves were found from cultured pineal organ homogenates or recombinant AANAT2 enzymes. There is no effect of temperature on the stage and period of the circadian rhythm in the case of fish pike (Falcon et al. 1994).

Thus, the synchronized photoperiod action that regulates the period of the melatonin signal and the temperature that governs its amplitude is supposed to deliver accurate definitions of both the diurnal and annual cycles. The temperature changes related to global warming and husbandry condition may have dramatic effects on the time-keeping system of fish. Melatonin is the principal hormonal secretion of the pineal organ. The involvement of the control process in daily and seasonal rhythms is widely acknowledged but not fully demonstrated yet. The daily rhythms in fish by melatonin/pineal organs involve food intake, locomotion of activity, thermal preference, skin pigmentation, vertical migration, rest and shoaling behavior, growth, reproduction, and annual processes, including for migrating salmonids (Falcón et al. 2007).

6 Effects of Melatonin on Fishes

A previous study deals with the effect of photoperiod manipulation, melatonin treatment, and/or pinealectomy, which led to contradictory assumptions concerning the part melatonin plays in regulating neuroendocrine (Bromage et al. 2001; Falcón et al. 2007). The reason is that the studies were carried out under various experimental trials (the time of the experiment was crucial), within the same or different species, historical status, and animals of other sex. Melatonin mediates the effects of photoperiod by coming to light on numerous neuroendocrine and behavioral functions. In wholly developed gonads in fish, in vitro release of LH from pituitary cells in culture stimulates the low concentrations of melatonin; in vivo, melatonin causes significant elevations in LH in plasma late throughout the photo phase of the day-night cycle, when managed in the basal diencephalon.

For larvae's development, minimal light intensity is needed for normal growth and development. In diurnal fish species, the case of older fish also responds to photoperiod manipulations; long days largely influence growth performance. “Day length” and “food availability” are essential for the growth and development of the fish effect synergistically.

In the hypothalamus of cultured carp species, melatonin causes a reduction in the level of dopamine, which results in an amplified secretion of LHb (Popek et al. 2006). Melatonin's critical role in the regulation of the annual testicular action was achieved from studies in *Catla Catla* (Bhattacharya et al. 2007). The action of Maturational inducing hormone (MIH) increases up to 4 h earlier in the incubation medium due to the addition of melatonin (Chattoraj et al. 2005); conversely, serotonin hinders the MIH actions as well as a dose of melatonin on the MIH induced the carp oocyte maturation (Chattoraj et al. 2005).

Generally, larvae need a minimum intensity of light for development and normal growth. Old fish also react to photoperiod manipulation; naturally, growth is stimulated in diurnal fish species by longer days. Food availability and the day's length are essential and synergistically affected. Food intake, digestion, and growth are specific behavioral rhythms, and reproduction and controlling the pineal organ or melatonin are thought to operate here (Ekström and Meissl 1997). But the results are often conflicting. For example,

1. Melatonin administration i.p. for a short time to goldfish, but not long, usually several days, causes an increase in growth and weight gain (De Vlaming 1980).
2. Increased weight gain after melatonin inserts in Atlantic salmon parr (Salmo salar; Porter et al. 1999); however, it reduces the body weight and growth rate in trout (Taylor et al. 2005). Keeping in view from a feeding point of view, it has been found to reduce fish's food intake by acute treatments of melatonin (López-Olmeda et al. 2006), but fish grow differently subject to the diurnal time feeding.

In vitro, it was challenged with physiological concentrations of melatonin in trout pituitary, which released increasing levels of GH (Falcón et al. 2003).

The precursor of melatonin is serotonin, which plays a direct role in locomotion activities responses in different species of fish and contributes to the synchronization of these everyday activities. Therefore, in sockeye salmon, serotonin amplified locomotor activity mainly only during the dark period, while during the light phase, melatonin decreases the locomotory activity (Byrne 1970). The supplementation of melatonin also reduces the overall activity of locomotion in sea bass (Herrero et al. 2007) to encourage surfacing behavior in goldfish and to endorse sleep (Zhdanova et al. 2001) to decrease aggressiveness responses of the cichlid fish *Aequidens pulcher* (Munro 1986). In fish, melanin has various functions like pigmentation, immunity, skin protection, and stress responses (Kittilsen et al. 2009). Another melanin-concentrating hormone (Mch) released by the brain, regulates variations in body color involving controlling the dispersion and cohesion of melanin in the chromophore (Baker et al. 1995).

7 Color Changes

The color changes of fish are by two mechanisms: physiological and morphological.

7.1 Physiological Color Changes

The physiological color change is due to and is related to the dispersion and aggregation of granules of pigments (chromatosomes) of chromatophores in the skin (Sköld et al. 2016) or variations in the distance and angle among light-reflecting platelets in motile iridophores (Fujii 2000). Both endocrine and sympathetic systems control the physiological color change in fish. In the case of the sympathetic nervous system, noradrenalin has been inducing chromatosome aggregation, while many hormones are involved in pigmentation. Melanin-concentrating hormones (Mch1 and Mch2) play an essential role in pigment accumulation (Mizusawa et al. 2013). The dispersion of pigment granules is encouraged by melanocyte-stimulating hormone (Msh) (Fujii 2000; Yamanome et al. 2007).

Another hormone, adrenocorticotropic hormone (Acth), which is mainly involved in stress-related responses (Wendelaar Bonga 1997), has been found to have the capability to disperse chromatosomes (Fujii 2000). Melatonin act as a chromatosome aggregator (Aspengren et al. 2012; Sköld et al. 2008) involved in color change and dispersing of pigment effect in xanthophores and erythrophores prolactin (Fujii 2000; Sköld et al. 2008). MCH and noradrenalin are generally released on light backgrounds during physiological color change. By contrast, the level of α-Msh in plasma is amplified on dark backgrounds (Sugimoto 2002; Mizusawa et al. 2013).

Remarkably, the degree of acetylation can control the α-Msh dispersion ability. Monoacetyl-α-Msh dispersed the pigment, which has been reported in tilapia *Oreochromis mossambicus*, Japanese flounder *Paralichthys olivaceus*, goldfish *Carassius auratus*, and barfin flounder *Verasper moseri* (Kobayashi et al. 2012; van der Salm et al. 2005). α-Msh also shows the high capacity of dispersion pigment during deacetylation in xanthophores of goldfish (Kobayashi et al. 2012), and the capability of dispersion of desacetyl-α-Msh has also been found in both Japanese flounder and barfin (Kobayashi et al. 2011).

7.2 Morphological Color Changes

Color change morphologically is caused by long-term stimuli. It is mediated by apoptosis or the skin chromatophores' proliferation and changes in their amount of pigment and morphology (Sköld et al. 2016). Several studies have confirmed fish color change due to increasing or decreasing number, morphology, and melanophore size adaptation under long-term light or dark background (van der Salm et al. 2005).

In vivo, α-Msh long-term treatment promotes and increases the density of melanophore in tilapia (Van Eys and Peters 1981) and barfin flounder (Yamanome et al. 2007), and in trout level of plasmatic α-Msh is high during black background adaptation. Interestingly, the dynamics of plasmatic α-Msh levels during background adaptation are not similar in all the species (Baker et al. 1986; Mizusawa et al. 2013; van der Salm et al. 2005). Due to the existence of different isoforms of α-Msh with varying strengths of bioactivity, possibly by multiple endocrine control in fish, or role of α-Msh, an adaptation of background may differ from species to species (Leclercq et al. 2010).

8 Environmental Factors Affecting Color Change

8.1 Light

Chromatophores act instantly to an incident of light. The "responses of primary color" can be seen during the development of the embryo and stages of larval rearing, when chromatophores are not stimulated or under endocrine control, as well as in adulthood regardless of the presence of both nervous and endocrine systems (Fujii 2000).

Usually, the response of melanophores varies between 380 and 580 nm wavelengths by dispersing of melanosomes (Chen et al. 2013), and erythrophores accumulate or spread pigment depending on exposure to wavelengths (short or medium) (Sato et al. 2004; Chen et al. 2013).

The photo response of iridophores depends on the intensity of incident light. The highest photoresponsivity is observed with a wavelength of 500 (Kasai and Oshima 2006). Also, the photic environment affects fish pigmentation by regulating endocrine and nervous systems. To date, very few studies have been conducted on the effect of different types of wavelengths on the pigmentation of fish. Thus, there is a broad scope for research in this area.

Light Intensity

Luminescence has been known to affect the behavior of fish, growth, physiology, and coloration in various fish species, such as *Paralichthys woolmani* (Han et al. 2005). Santos et al. (2019) demonstrated the effect of light on food intake, food conversion, behavior, and cortisol level plasma of *Lophiosilurus alexandri* juveniles. However, no skin pigmentation effect was reported.

Melanogenesis is incited by light, and the synthesis of melanophore increases, resulting in darker body coloration (Odiorne 1957). Various studies have been conducted to study the effects of light intensity on body growth, coloration, survival rate, swimming behavior, feeding patterns, and other physiological activity (Batty et al. 1990; Reichard et al. 2002; Richmond et al. 2004; Lee et al. 2017).

Depending on the environmental condition, some fish may change their color, behavior, and physiology to protect themselves from predators (Mizusawa et al. 2013). This property is called camouflage, making it difficult for them to be spotted. Photo receptivity in environments may change according to their developmental stage (Boeuf and Le Bail 1999). It is reported that the absence of light increases the growth of catfish larvae (Brito and Pienaar 1992; Han et al. 2005; Kitagawa et al. 2015). While cleaning care should be taken, since this behavior species is to remain in the bottom of the aquarium; its visualization default. The ideal light intensity level may improve fish growth without causing stress.

The body color of cultured fish tends to reduce in quality compared to wild fish (Booth et al. 2004), which is problematic because the values of cultured fish commercially decrease. The rearing and culturing of fish under different light intensities affect their body color. To conclude this, fish are cultured under different intensities of light conditions and examined for the occurrence of expression of genes related to the melanin and changes in body color radiance.

Melanin plays multiple roles in fish, including, among others, immunity, protection of skin, pigmentation, and responsiveness to stress (Amiya et al. 2008; Kittilsen et al. 2009; Cal et al. 2017). Melanin-concentrating hormone (MCH) changes body color by controlling the dispersion and cohesion of melanin in the chromophore (Baker et al. 1995). If the light intensity is stronger, MCH mRNA is highly expressed.

- Coldwater fishes are generally color-wise best in the autumn and winter when the low temperature causes the pigment in a chromophore to scatter throughout the cell. During mid-summer, when temperatures are high, the reverse occurs, and the fish color appears less intense.
- Goldfish and Koi, which live in ponds rich in algae for some time, are observed to be intensely colored due partly to the lower photic conditions and partly to the algae's impact on the water.

The darkening of the skin observed was due to an increase in the concentration of melanin compared with that of fish held under the intensity of low light. The intensity of light at the surface of the water of a cage with sunshine is higher than the intensities of light used in our laboratory experiment, and this is a significant reason for the observed higher hypermelanosis reared in floating cages in red porgies (Kolios et al. 1997).

Photoperiod

Photoperiod is an essential factor that can also cause changes in skin color; melatonin not only acts directly over chromatophores but also changes other pathways of the endocrine that affect the pigmentation of the skin. In neon tetra, erythrophores and melanophores produced red and brown colors, reduced at night, indicating the color regulation by an endogenous circadian rhythm (Lythgoe and Shand 1982). The skin pigmentation differences due to daylength were also reported during the larval development of Japanese flounder after metamorphosis when comparing the effects of continuous illumination (LL) to natural light conditions (Mizutani et al. 2020). Lyon and Baker (1993) also described that in rainbow trout, MCH secretion reached a peak during the photoperiod, and then it slowly reduced before night when the lowest concentrations were observed. The skin paleness color of animals is directly related to hormonal differences.

8.2 Water Temperature

Water temperature is a vital environmental factor for cold-blooded animals' metabolism, homeostasis, growth, and development. Many ectotherms are dark-colored when cold and lighten when warmed (Norris 1967; Kats and Van Dragt 1986; Sherbrooke and Frost 1989). Fernandez and Bagnara (1991) observed that frogs, *Rana chiricahuensis*, held in gray backgrounds and exposed to low temperature (5 ° C) were significantly darker in both the ventral and dorsal side of the skin area than frogs held at 25 °C temperature. However, in the same study, it was reported that there was no water temperature effect on the skin color of *Rana pipiens.* Also, it was concluded that dark coloration stimulates cryptic behavior and/or enhances absorption of solar radiation; hence the achievement facilitates more temperature of the body for the normal activity of the animal (Norris 1967; Fernandez and Bagnara 1991).

Other factors like crowding, handling, transportation, hydrostatic pressure, temperature change, salinity, and oxygen difference can affect chromatophores' physiology and thus alter fish pigmentation. Some of these stimuli have a direct effect on chromatophores and are less studied, though it is accepted that higher temperatures accumulate chromatosomes while they spread at lower temperatures (Fujii and Oshima 1994).

8.3 Tank Color

In aquaculture, structures of rearing tanks are a significant factor to be considered since it has been reported that they can cause stress on fish (Ishibashi et al. 2013), and have an effect on growth and survival of the fish (Martinez-Cardenas and Purser 2011; Wang et al. 2017), lead to anomalies of the skeletal system (Cobcroft and Battaglene 2009), and also have an effect on the behavior of fish (Cobcroft and Battaglene 2009) and skin coloration (van der Salm et al. 2005; Eslamloo et al. 2015). Background adaptation is observed mainly in fish and infers the capability to body color change in response to environmental luminance, as in the case of dark or fluorescent backgrounds. This characteristic is utilized in aquaculture to enhance the pigmentation of the skin.

In the case of goldfish, red and blue backgrounds are always stressful, whereas a white background improves the growth of fish but causes a loss of skin color (Eslamloo et al. 2015). Dark-colored tanks in *Lophiosilurus alexandri* supported an increase in the level of plasma cortisol. They reduce the skin brightness while using light colors leads to lighter skin color (Costa et al. 2017).

The adaptation to black background resulted in pigment spread in melanophores within a few hours, associated with increased plasma melanocyte-stimulating hormone (α-MSH) levels (Mizusawa et al. 2013). Arends et al. (2000) observed that gilthead sea bream adapted to a white background for 15 days showed a rise in the level of α-MSH in plasma compared to those adapted to black or gray backgrounds.

9 Hormone Regulators

Teleost fish, unlike other vertebrates, exhibits a dual hormonal mechanism for regulating skin color (Bertolesi et al. 2019). Two hormones with antagonistic effects, skin lighting and darkening, have been presented as significant physiological and morphological changes in color regulators. These two hormones, melanin-concentrating hormone (MCH) and melanocyte-stimulating hormone (MSH), are derived from proopiomelanocortin.

10 Neuronal Control

The sympathetic postganglionic systems control the speedy chromatosomes conglomeration. The cells in the eyes capture the chromatic signals through the optic tectum and motoneurons in the medulla and are processed to chromatophores via direct nervous connections (Grove 1994; Fujii 2000). The noradrenaline hormone from nerve terminals surges or declines, reliant on diverse stimuli (Fujii and Oshima 1994). Other research revealed that ATP acts as a co-transmitter along with noradrenaline hormone. In the synaptic cleft, it is dephosphorylated to adenosine, which works for more extended periods and opposites noradrenaline action, causing re-scattering of pigment after the finish of the stimulus (Fujii and Oshima 1994).

11 Impact of Malpigmentation on Aquaculture

In commercial fish production, malpigmentation is a common problem and common cause of loss of aquaculture. Several species have been reported with abnormal pigmentation, such as flatfish (Akyol and Şen 2012; Macieira et al. 2006). In flatfish, characteristics of normal pigmentation are a high number of melanophores on the ocular side, and on the blind side the number of melanophores is low (Bolker and Hill 2000). Common pigment defects in flatfish are:

- Albinism, hypomelanosis, or pseudo-albinism: the complete absence of pigmentation to white areas on the ocular side (Bolker and Hill 2000).
- Hypermelanosis: complete pigmentation to blind-side pigmented areas (Bolker and Hill 2000).

The defects of pigment are not restricted to cultured fish. Several cases of malpigmented adults in the wild have been reported in various flatfish species like common sole *Solea solea* (Akyol and Şen 2012; Cerim et al. 2016) and lined sole *Achirus lineatus* (Macieira et al. 2006). The highest pigmented abnormalities are reported in the case of flatfish (Bolker and Hill 2000).

12 Pigment Abnormalities

In the fish, the pigment complexity pattern makes it difficult to reduce the probability of pigment defects occurring in aquaculture species—generally, two hypotheses to explain the pigment abnormalities in flatfish.

13 Based on Nutrition

The deficiency of nutrition during the development of larvae causes visual defects, which affect the endocrine signaling pathway, which is necessary for the differentiation of melanophores. Deficient ratios of essential fatty acids (EPA, DHA) and vitamin A produce rhodopsin malformation in the eyes of flatfish (Kanazawa 1993). Some studies reported that the normal and abnormal tissue of neurons is affected by the Content of EPA and DHA (Estevez and Kanazawa 1996). The deficient intake of fatty acids and amino acids alters neural and eye degeneration in flatfish (Estevez et al. 1997).

First hypothesis: The pathway of signal to the central nervous system (CNS) from the retina could be disturbed by deficiencies in nutrition. The inappropriate α-Msh production from the pituitary gland might cause nutritional deficiencies, which could produce abnormalities of the pigment in flatfish (Bolker et al. 2005). Metamorphosis process like pigmentation in fish larvae, can interfere with iodine levels which causes a decrease in the level of the thyroid hormone (Th) level (Hamre et al. 2005; Wang et al. 2019).

The interaction between vitamin A and fatty acids and also the interaction between vitamin A and thyroid hormone are key nutrients for the stimulation of normal pigmentation, at the nuclear receptor level (Hamre et al. 2005). A high dose of retinoic acid stimulating the development of chromatophore in flatfish of blind side is influenced by vitamin A (Miwa and Yamano 1999).

Many fish species own their bright coloration to carotenoids, which are the predominant pigments in erythrophores and xanthophores. Thus, carotenoid must be obtained from the diet, de novo, fish is not able to biosynthesize (Bjerkeng 2008). Several culture species required carotenoid supplementation to avoid skin paleness (Bjerkeng 2008).

Most of the carotenoid used in aquaculture is astaxanthin in feeds, and their sources are obtained from chemical synthesis, from algae, fungi, bacteria, and yeast (Lim et al. 2018). In addition, astaxanthin is a source of pinkish-red pigments also to improve growth, survival, tolerance of stress, reproductive performance, disease resistance, and gene expression of immune-related genes (Lim et al. 2018).

14 Based on Genetics

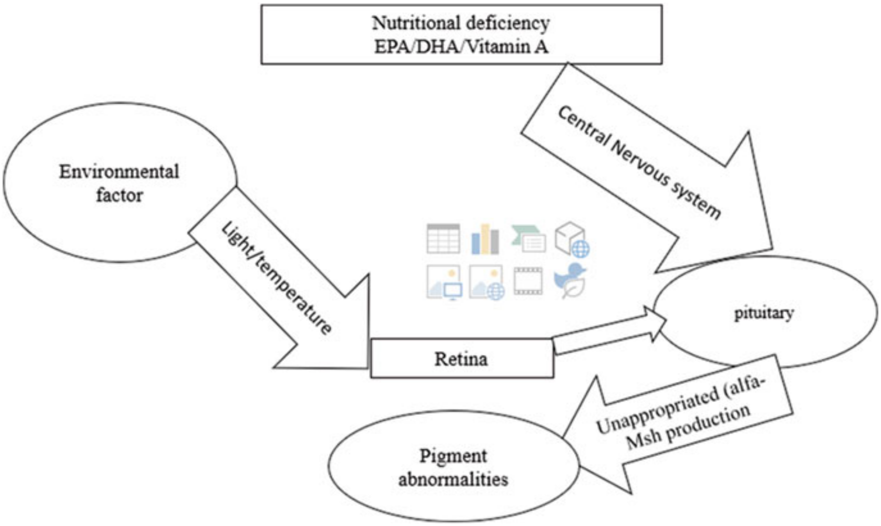
The second hypothesis proposes that the pigmentation defects during larval metamorphosis are responsible for the deregulation of the blind-side and ocular structures of skin in the flatfish (Seikai and Matsumoto 1994). Normal malpigmented, pigmented skin, and abnormalities of pigment histologically analyzed on the incorrect side may be caused by the normal regulatory pathway (Bolker et al. (2005).

Several other genes are responsible and also deregulate the defects of pigmentation in adults flatfish (Darias et al. 2013; Guillot et al. 2012). In malpigmented fish, asip1 gene is commonly more expressed in blind-side skin and is deregulated. Guillot et al. (2012) noted that the levels of asp1 are higher in ocular-side light spots and are similar to blind-side.

The cause of malpigmentation is due to nutritional imbalance of sole fish larvae is accompanied by upregulation of asip1 mRNA in comparison to normally pigmented fish (Darias et al. 2013). The potential cause of pseudo-albinism is downregulation of asip1 (Darias et al. 2013; Guillot et al. 2012). However, the regulation of asip1 seems to have a crucial role in abnormalities of fish pigment.

In malpigmented flatfish, additional genes also have been seen to be deregulated. For example, Darias et al. (2013) suggested that, surprisingly, in pseudo-albino sole differentiation of melanophore is stimulated by somatolactin (SL) gene upregulation, which is implicated in differentiation of melanophore (Fukamachi et al. 2009). Other genes are also involved in the development of melanocyte, like paired box protein 3 (pax3) (Kubic et al. 2008) and tyrosinase (tyr) gene. The master regulator gene considered for melanogenesis is mitf gene (García et al. 2005).

Both hypotheses reveal the effect of various mechanisms and regulation of melanocortin systems by different melanogenic genes (Bolker and Hill 2000).



15 Conclusion

Quality criteria of the fish decide the market value for both the consumption for humans and also use for ornamental purposes. The natural skin color can be negatively affected by the rearing condition, nutrition quality, color of tank, light intensity and duration of light, interaction of light and social interaction. The pattern of skin pigmentation in fish is species-specific and depends on the number and types of chromatophores. Recent studies have identified the change in color by the control of the endocrine and nervous system. Some regulators like the melanocortin system and melanogenic genes, such as Sl, Asip, and Th, seem to play an important role in the regulation of pigmentation. Pigmentation pattern can be improved by utilization of feed additives like carotenoids so future studies associated with the mechanism behind the absorption of carotenoids and sources of other types of additives and sources of pigment for the farmer and entrepreneurs are required. Future studies are needed to identify the pigmentation related to control endocrine factors that are being modulated when fish are reared under suboptimal conditions.

References

Akyol O, Şen H (2012) First record of abnormal pigmentation in a wild common sole, Solea solea L., from the Aegean Sea. Turkish J Vet Anim Sci 36:727–729. https://doi.org/10.3906/vet1110-7

Amiya N, Amano M, Iigo M, Yamanome T, Takahashi A, Yamamori K (2008) Interaction of orexin/hypocretin-like immunoreactive neurons with melanin-concentrating hormone and α-melanocyte-stimulating hormone neurons in brain of a pleuronectiform fish, barfin flounder. Fish Sci 74:1040–1046

Arends R, Rotllant J, Metz J, Mancera JM, Bonga SW, Flik G (2000) Alpha-MSH acetylation in the pituitary gland of the sea bream (Sparus aurata L.) in response to different backgrounds, confinement and air exposure. J Endocrinol 166:427–435. https://doi.org/10.1677/joe.0.1660427

Aspengren S, Hedberg D, Sköld HN, Wallin M (2012) New insights into melanosome transport in vertebrate pigment cells. In: Jeon K (ed) International review of cell and molecular biology, vol 293, 1st edn. Elsevier, Amsterdam, pp 245–302

Baker BI, Bird DJ, Buckingham JC (1986) Effects of chronic administration of melanin-concentrating hormone on corticotrophin, melanotrophin, and pigmentation in the trout. Gen Comp Endocrinol 63:62–69

Baker B, Levy A, Hall L, Lightman S (1995) Cloning and expression of melanin-concentrating hormone genes in the rainbow trout brain. Neuroendocrinology 61:67–76

Batty RS, Blaxter JHS, Richard JM (1990) Light intensity and the feeding behavior of herring, *Clupea harengus*. Mar Biol 107:383–388

Belton B, Bush SR, Little DC (2018) Not just for the wealthy: rethinking farmed fish consumption in the Global South. Glob Food Sec 16:85–92. https://doi.org/10.1016/j.gfs.2017.10.005

Benyassi A, Schwartz C, Ducouret B, Falcon J (2001) Glucocorticoid receptors and serotonin N-acetyltransferase activity in the fish pineal organ. Neuroreport 12:889–892. https://doi.org/10.1097/00001756-200104170-00004

Bertolesi GE, Zhang JZ, McFarlane S (2019) Plasticity for colour adaptation in vertebrates explained by the evolution of the genes pomc, pmch and pmchl. Pigment Cell Melanoma Res 32:510–527. https://doi.org/10.1111/pcmr.12776

Bhattacharya S, Chattoraj A, Maitra SK (2007) Melatonin in the regulation of annual testicular events in carp Catla catla: evidence from the studies on the effects of exogenous melatonin, continuous light, and continuous darkness. Chronobiol Int 24(4):629–650

Bjerkeng B (2008) Carotenoids in aquaculture: fish and crustaceans. In: Britton G, Liaaen-Jensen S, Pfander H (eds) Carotenoids. Birkhäuser, Basel, pp 237–254

Boeuf G, Le Bail P-Y (1999) Does light have an influence on fish growth? Aquaculture 177:129–152

Bolker JA, Hill CR (2000) Pigmentation development in hatchery-reared flatfishes. J Fish Biol 56:1029–1052. https://doi.org/10.1006/jfbi.2000.1260

Bolker JA, Hakala TF, Quist JE (2005) Pigmentation development, defects, and patterning in summer flounder (Paralichthys dentatus). Zoology 108:183–193. https://doi.org/10.1016/j.zool.2005.05.001

Booth MA, Warner-Smith RJ, Allan GL, Glencross BD (2004) Effects of dietary astaxanthin source and light manipulation on the skin colour of Australian snapper Pagrus auratus (Bloch & Schneider 1801). Aquac Res 35:458–464

Brito PJ, Pienaar AG (1992) Laboratory experiments on the effect of light and cover on the behavior and growth of African catfish, Clarias gariepinus (Pisces: Clariidae). J Zool 227:43–62

Bromage NR, Porter MJR, Randall CF (2001) The environmental regulation of maturation in farmed finfish with special reference to the role of photoperiod and melatonin. Aquaculture 197:63–98

Byrne JE (1970) Locomotor activity responses in juvenile sockeye salmon, Oncorhynchus nerka, to melatonin and serotonin. Can J Zool 48(6):1425–1427

Cal L, Suarez-Bregua P, Cerdá-Reverter JM, Braasch I, Rotllant J (2017) Fish pigmentation and the melanocortin system. Comp Biochem Physiol A Mol Integr Physiol 211:26–33. https://doi.org/10.1016/j.cbpa.2017.06.001

Ceinos RM, Guillot R, Kelsh RN et al (2015) Pigment patterns in adult fish result from superimposition of two largely independent pigmentation mechanisms. Pigment Cell Melanoma Res 28:196–209. https://doi.org/10.1111/pcmr.12335

Cerim H, Celík M, Yapici S (2016) Occurrence of colour abnormalities and morphological aberration in common sole Solea solea (L., 1758) captured from the Aegean Sea. Cah Biol Mar 57:85–87

Chattoraj A, Bhattacharyya S, Basu D, Bhattacharya S, Bhattacharya S, Maitra SK (2005) Melatonin accelerates maturation inducing hormone (MIH): induced oocyte maturation in carps. Gen Comp Endocrinol 140(3):145–155

Chen SC, Robertson RM, Hawryshyn CW (2013) Possible involvement of cone opsins in distinct photoresponses of intrinsically photosensitive dermal chromatophores in tilapia Oreochromis niloticus. PLoS One 8(8):e70342. https://doi.org/10.1371/journal.pone.0070342

Cobcroft JM, Battaglene SC (2009) Jaw malformation in striped trumpeter Latris lineata larvae linked to walling behavior and tank color. Aquaculture 289:274–282. https://doi.org/10.1016/j.aquaculture.2008.12.018

Costa DC, Mattioli CC, Silva WS, Takata R, Leme FOP, Oliveira AL, Luz RK (2017) The effect of environmental colour on the growth, metabolism, physiology and skin pigmentation of the carnivorous freshwater catfish Lophiosilurus alexandri. J Fish Biol 90:922–935. https://doi.org/10.1111/jfb.13208

Darias MJ, Andree KB, Boglino A et al (2013) Morphological and molecular characterization of dietary-induced pseudo-albinism during post-embryonic development of Solea senegalensis (Kaup, 1858). PLoS One 8:e68844. https://doi.org/10.1371/journal.pone.0068844

de Vlaming V (1980) Effects of pinealectomy and melatonin treatment on growth in the goldfish, *Carassius auratus*. Gen Comp Endocrinol 40:245–250. https://doi.org/10.1016/0016-6480(80)90130-6

Ekström P, Meissl H (1997) The pineal organ of teleost fishes. Rev Fish Biol Fish 7:199–284

Eslamloo K, Akhavan SR, Eslamifar A, Henry MA (2015) Effects of background colour on growth performance, skin pigmentation, physiological condition and innate immune responses of goldfish, Carassius auratus. Aquac Res 46:202–215. https://doi.org/10.1111/are.12177

Estevez A, Kanazawa A (1996) Fatty acid composition of neural tissues of normally pigmented and unpigmented juveniles of Japanese flounder using rotifer and Artemia enriched in n-3 HUFA. Fish Sci 62:88–93. https://doi.org/10.2331/fishsci.62.88

Estevez A, Sameshima M, Ishikawa M et al (1997) Effect of diets containing low levels of methionine and oxidized oil on body composition, retina structure and pigmentation success of Japanese flounder. Aquac Nutr 3:201–216. https://doi.org/10.1046/j.1365-2095.1997.00092.x

Falcon J (1999) Cellular circadian clocks in the pineal. Prog Neurobiol 58:121–162

Falcon J, Bolliet V, Ravault JP, Chesneau D, Ali MA, Collin JP (1994) Rhythmic secretion of melatonin by the superfused pike pineal organ: thermos and photoperiod interaction. Neuroendocrinology 60:535–543

Falcón J, Besseau L, Fazzari D, Attia J, Gaildrat P, Beauchaud M, Boeuf G (2003) Melatonin modulates secretion of growth hormone and prolactin by trout pituitary glands and cells in culture. Endocrinology 144(10):4648–4658

Falcón J, Besseau L, Sauzet S, Boeuf G (2007) Melatonin effects on the hypothalamo–pituitary axis in fish. Trends Endocrinol Metab 18(2):81–88

Fernandez PJ, Bagnara JT (1991) Effect of background color and low temperature on skin color and circulating ά-MSH in two species of leopard frog. Gen Comp Endocrinol 83:132–141

Fujii R (2000) The regulation of motile activity in fish chromatophores. Pigment Cell Res 13:300–319. https://doi.org/10.1034/j.1600-0749.2000.130502.x

Fujii R, Oshima N (1994) Factors influencing motile activities of fish chromatophores. In: Advances in comparative and environmental physiology. Springer, Berlin, pp 1–54

Fukamachi S, Yada T, Meyer A et al (2009) Effects of constitutive expression of somatolactin alpha on skin pigmentation in medaka. Gene 442:81–87. https://doi.org/10.1016/j.gene.2009.04.010

García-Borrón JC, Sánchez-Laorden BL, Jiménez-Cervantes C (2005) Melanocortin-1 receptor structure and functional regulation. Pigment Cell Res 18:393–410. https://doi.org/10.1111/j.1600-0749.2005.00278.x

Grove DJ (1994) Chromatophores. In: Nilsson S, Holmgren S (eds) Comparative physiology and evolution of the autonomic nervous system. Harwood Academic Publishers, Chur, pp 331–352

Guillot R, Ceinos RM, Cal R et al (2012) Transient ectopic overexpression of agouti-signalling protein 1 (Asip1) induces pigment anomalies in flatfish. PLoS One 7:e48526. https://doi.org/10.1371/journal.pone.0048526

Hamre K, Moren M, Solbakken J, Opstad I, Pittman K (2005) The impact of nutrition on metamorphosis in Atlantic halibut (Hippoglossus hippoglossus L.). Aquaculture 250:555–565. https://doi.org/10.1016/j.aquaculture.2005.01.016

Han D, Xie SH, Lei W, Zhu X, Yang Y (2005) Effect of light intensity on growth, survival and skin color of juvenile Chinese longsnout catfish (Leiocassis longirostris Gunther). Aquaculture 248: 299–306

Harpaz S, Padowicz D (2007) Color enhancement in the ornamental dwarf cichlid Microgeophagus ramirezi by addition of plant carotenoids to the fish diet. Isr J Aquacult Bamid 59:195–200

Herrero MJ, Martínez FJ, Míguez JM, Madrid JA (2007) Response of plasma and gastrointestinal melatonin, plasma cortisol and activity rhythms of European sea bass (Dicentrarchus labrax) to dietary supplementation with tryptophan and melatonin. J Comp Physiol B 177(3):319–326

Ishibashi Y, Kurata M, Izumi T, Okada T (2013) Effects of tank wall pattern on survival, bone injury rate, and stress response of juvenile Pacific bluefin tuna, Thunnus orientalis. Aquac Eng 56:13–17. https://doi.org/10.1016/j.aquaeng.2013.03.004

Kanazawa A (1993) Nutritional mechanisms involved in the occurrence of abnormal pigmentation in hatchery-reared flatfish. J World Aquac Soc 24:162–166

Kasai A, Oshima N (2006) Light-sensitive motile iridophores and visual pigments in the neon tetra, Paracheirodon innesi. Zool Sci 23:815–819. https://doi.org/10.2108/zsj.23.815

Kats LB, Van Dragt RG (1986) Background color-matching in the spring peeper, Hyla crucifer. Copeia 1:109–115

Kawaguti S (1965) Electron microscopy on iridophores in the scale of the blue wrasse. Proc Jpn Acad 41:610–613

Kitagawa AT, Costa LS, Paulino RR, Luz RK (2015) Feeding behavior and the effect of photoperiod on the performance and hematological parameters of the pacama catfish (Lophiosilurus alexandri). Appl Anim Behav Sci 1:1–34

Kittilsen S, Schjolden J, Beitnes-Johansen I, Shaw JC, Pottinger TG, Sørensen C et al (2009) Melanin-based skin spots reflect stress responsiveness in salmonid fish. Horm Behav 56(3): 292–298

Kobayashi Y, Chiba H, Mizusawa K, Suzuki N, Cerdá-Reverter JM, Takahashi A (2011) Pigment-dispersing activities and cortisol-releasing activities of melanocortins and their receptors in xanthophores and head kidneys of the goldfish Carassius auratus. Gen Comp Endocrinol 173: 438–446. https://doi.org/10.1016/j.ygcen.2011.06.019

Kobayashi Y, Mizusawa K, Saito Y, Takahashi A (2012) Melanocortin systems on pigment dispersion in fish chromatophores. Front Endocrinol 3(9):884. https://doi.org/10.3389/fendo.2012.00009

Kolios P, Kiritsis S, Katribusas N (1997) Larval-rearing and growout of the red porgy (Pagrus pagrus) in the Riopesca hatchery (Greece). Hydrobiologia 358:321–325

Kubic JD, Young KP, Plummer RS et al (2008) Pigmentation PAX-ways: the role of Pax3 in melanogenesis, melanocyte stem cell maintenance, and disease. Pigment Cell Melanoma Res 21:627–645. https://doi.org/10.1111/j.1755-148X.2008.00514.x

Leclercq E, Taylor JF, Migaud H (2010) Morphological skin colour changes in teleosts. Fish Fish 11:159–193. https://doi.org/10.1111/j.1467-2979.2009.00346.x

Lee JS, Britt LL, Cook MA, Wade TH, Berejikian BA, Goetz FW (2017) Effect of light intensity and feed density on feeding behaviour, growth and survival of larval sablefish *Anoplopoma fimbria*. Aquac Res 48:4438–4448

Lim KC, Yusoff FM, Shariff M, Kamarudin MS (2018) Astaxanthin as feed supplement in aquatic animals. Rev Aquacult 10:738–773. https://doi.org/10.1111/raq.12200

López-Olmeda JF, Madrid JA, Sánchez-Vázquez FJ (2006) Melatonin effects on food intake and activity rhythms in two fish species with different activity patterns: diurnal (goldfish) and nocturnal (tench). Comp Biochem Physiol A Mol Integr Physiol 144(2):180–187

Lyon VE, Baker BI (1993) The effect of photoperiod on plasma levels of melanin-concentrating hormone in the trout. J Neuroendocrinol 5(5):493–499

Lythgoe JN, Shand J (1982) Changes in spectral reflexions from the iridophores of the neon tetra. J Physiol 325:23–34

Macieira RM, Joyeux JC, Chagas LP (2006) Ambicoloration and morphological aberration in the sole Achirus declivis (Pleuronectiformes: Achiridae) and two other cases of color abnormalities in achirid soles from southeastern Brazil. Neotrop Ichthyol 4:287–290. https://doi.org/10.1590/S1679-62252006000200016

Martinez-Cardenas L, Purser GJ (2011) Effect of temperature on growth and survival in cultured early juvenile pot-bellied seahorses, Hippocampus abdominalis. J World Aquacult Soc 42:854–862. https://doi.org/10.1111/j.1749-7345.2011.00526.x

Miwa S, Yamano K (1999) Retinoic acid stimulates development of adult-type chromatophores in the flounder. J Exp Zool 284:317–324. https://doi.org/10.1002/(SICI)1097-010X(19990801)284:33.0.CO;2-B

Mizusawa K, Kobayashi Y, Yamanome T, Saito Y, Takahashi A (2013) Interrelation between melanocyte-stimulating hormone and melanin-concentrating hormone in physiological body color change: roles emerging from barfin flounder 972 Verasper moseri. Gen Comp Endocrinol 181:229–234. , 973. https://doi.org/10.1016/j.ygcen.2012.09.026

Mizutani K, Yamada T, Suzuki KW et al (2020) Prevention of hypermelanosis by rearing Japanese flounder *Paralichthys olivaceus* in net-lined tanks. Fish Sci 86:127–136. https://doi.org/10.1007/s12562-019-01369-1

Munro AD (1986) Effects of melatonin, serotonin, and naloxone on aggression in isolated cichlid fish (Aequidens pulcher). J Pineal Res 3(3):257–262

Norris KS (1967) Color adaptations in desert reptiles and its thermal relationships. In: Milstead WW (ed) Lizard ecology: a symposium. University of Missouri Press, Columbia, pp 162–229

Odiorne JM (1957) Color changes. In: Brown ME (ed) The physiology of fishes, vol 2. Academic, New York, pp 387–401

Olsson M, Stuart-Fox D, Ballen C (2013) Genetics and evolution of colour patterns in reptiles. Semin Cell Dev Biol 24:529–541. https://doi.org/10.1016/j.semcdb.2013.04.001

Parichy DM, Elizondo MR, Mills MG et al (2011) Normal table of postembryonic zebrafish development: staging by externally visible anatomy of the living fish. Dev Dyn 238:2975–3015. https://doi.org/10.1002/dvdy.22113.Normal

Parker AR, Martini N (2006) Structural colour in animals—simple to complex optics. Opt Laser Technol 38:315–322. https://doi.org/10.1016/j.optlastec.2005.06.037

Popek W, Luszczek-Trojnar E, Drag-Kozak E, Rzasa J, Epler P (2006) Effect of melatonin on dopamine secretion in the hypothalamus of mature female common carp, Cyprinus carpio L. Acta Ichthyol Piscat 2(36):135–141

Porter MJR, Duncan NJ, Mitchell D, Bromagea NR (1999) The use of cage lighting to reduce plasma melatonin in Atlantic salmon (*Salmo salar*) and its effects on the inhibition of grilsing. Aquaculture 176:237–244. https://doi.org/10.1016/S0044-8486(99)00113-1

Prum RO (2006) Anatomy, physics, and evolution of structural colors. In: Hill GE, McGraw KJ (eds) Bird coloration: mechanisms and measurements. Harvard University Press, Cambridge

Reichard M, Jurajda P, Ondračková M (2002) The effect of light intensity on the drift of young-of-the-year cyprinid fishes. J Fish Biol 61:1063–1066

Richmond HE, Hrabik TR, Mensinger AF (2004) Light intensity, prey detection and foraging mechanisms of age 0 year yellow perch. J Fish Biol 65:195–205

Roberts NW, Marshall NJ, Cronin TW (2012) High levels of reflectivity and pointillist structural color in fish, cephalopods, and beetles. Proc Natl Acad Sci U S A 109:E3387. author reply E3388. https://doi.org/10.1073/pnas.1216282109

Roulin A, Ducrest A-L (2013) Genetics of colouration in birds. Semin Cell Dev Biol 24:594–608. https://doi.org/10.1016/j.semcdb.2013.05.005

Rudh A, Qvarnström A (2013) Adaptive colouration in amphibians. Semin Cell Dev Biol 24:553–561. https://doi.org/10.1016/j.semcdb.2013.05.004

Santos TG, Schorer M, dos Santos JC, Pelli A, Pedreira MM (2019) The light intensity in growth, behavior and skin pigmentation of juvenile catfish Lophiosilurus alexandri (Steindachner). Lat Am J Aquat Res 47(3):416–422

Sato M, Ishikura R, Oshima N (2004) Direct effects of visible and UVA light on pigment migration in erythrophores of Nile tilapia. Pigment Cell Res 17:519–524. https://doi.org/10.1111/j.1600-0749.2004.00178.x

Seikai T, Matsumoto J (1994) Mechanism of pseudoalbinism in flatfish: an association between pigment cell and skin differentiation. J World Aquacult Soc 25:78–85

Sherbrooke WC, Frost SK (1989) Integumental chromatophores of a color-change, thermoregulating lizard, Phrynosoma modestum (Iguanidae; reptilia). American Museum novitates; no. 2943. American Museum Novitates, New York, pp 1–14

Sköld HN, Amundsen T, Svensson PA, Mayer I, Bjelvenmark J, Forsgren E (2008) Hormonal regulation of female nuptial coloration in a fish. Horm Behav 54:549–556. https://doi.org/10.1016/j.yhbeh.2008.05.018

Sköld HN, Aspengren S, Cheney KL, Wallin M (2016) Fish chromatophores—from molecular motors to animal behavior. In: International review of cell and molecular biology, vol 321. Academic, New York, pp 171–219. https://doi.org/10.1016/bs.ircmb.2015.09.005

Sugimoto M (2002) Morphological color changes in fish: regulation of pigment cell density and morphology. Microsc Res Tech 58:496–503. https://doi.org/10.1002/jemt.10168

Taylor JF, Migaud H, Porter MJR, Bromage NR (2005) Photoperiod influences growth rate and plasma insulin-like growth factor-I levels in juvenile rainbow trout, Oncorhynchus mykiss. Gen Comp Endocrinol 142(1–2):169–185

Van der Salm AL, Spanings FAT, Gresnigt R, Bonga SW, Flik G (2005) Background adaptation and water acidification affect pigmentation and stress physiology of tilapia, Oreochromis mossambicus. Gen Comp Endocrinol 144:51–59. https://doi.org/10.1016/j.ygcen.2005.04.017

Van Eys GJJM, Peters PTW (1981) Evidence for a direct role of α-MSH in morphological background adaptation of the skin in *Sarotherodon mossambicus*. Cell Tissue Res 217(2):361–372

Wang CA, Xu Q, Li J, Wang L, Zhao Z, Du X, Luo L, Yin J (2017) Effects of tank colour on growth and survival of taimen Hucho taimen (Pallas, 1773) larvae. Aquac Int 25:437–446. https://doi.org/10.1007/s10499-016-0041-x

Wang LM, Bu HY, Song FB, Zhu WB, Fu JJ, Dong ZJ (2019) Characterization and functional analysis of slc7a11 gene, involved in skin color differentiation in the red tilapia. Comp Biochem Physiol A 236:110529. https://doi.org/10.1016/j.cbpa.2019.110529

Wendelaar Bonga SE (1997) The stress response in fish. Physiol Rev 77:591–625. 1208. https://doi.org/10.1152/physrev.1997.77.3.591

Yamanome T, Chiba H, Takahashi A (2007) Melanocyte-stimulating hormone facilitates hypermelanosis on the non-eyed side of the barfin flounder, a pleuronectiform fish. Aquaculture 270:505–511. https://doi.org/10.1016/j.aquaculture.2007.05.037

Zhdanova IV, Wang SY, Leclair OU, Danilova NP (2001) Melatonin promotes sleep-like state in zebrafish. Brain Res 903:263–268. https://doi.org/10.1016/S0006-8993(01)02444-1

Climate Change and Stress Response in Teleost

Shivendra Kumar and Ankur Jamwal

Abstract

Fish being ectotherms and in direct contact with water are directly affected by climate change-induced hydrogeological changes and demonstrate a cascade of a response that ranges from cellular adaptation to change in population dynamics. In acute stress, a fish generally tends to increase ATP synthesis to fuel alarm reaction. However, a fish under chronic stress adapts its physiological functions to facilitate energy distribution in a manner that prioritizes the functioning of critical organs and essential cellular pathways. This chapter discusses the physiological processes involved in stress perception and adaptation. The role of the neuroendocrine system, the sympathetic nervous system-chromaffin cell axis (SNC), and the hypothalamus–pituitary–interrenal (HPI) axis is discussed in detail. Hydromineral balance and preservation of the functional structure of the protein in response to abiotic stress are also discussed.

Keywords

Climate change · Cortisol · Adaptation · Stress response · Chromaffin cells · Interrenal

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1 Introduction: Climate Change and Aquatic Systems

Climate change has significantly influenced the hydrological cycle. Altered precipitation and melting of snow and ice have influenced the quantity and seasonality of water fluctuations in the water bodies. There is an unequivocal effect of climate change on all types of water bodies, from high-altitude lakes to global ocean conveyor belts. In addition to the fluctuation of water level from precipitation and melting of glaciers, climate change in some manner has also increased the human consumption of water. This necessitates the construction of dams and water abstraction systems which has also altered the quantity of water in the river systems—posing stress to wild fish populations. The IPCC, 2022 report suggests that climate change will have a high impact on freshwater and oceanic ecosystem structures that will drive the species range shift and affect biodiversity (IPCC 2022).

Fish are ectotherms, making them vulnerable to global warming. This has led to an increasing interest among fish physiologists to study the effects of climate variables on fish and other ectotherms which can have direct value to the aquaculture industry or have implications for the understanding of adaptation physiology in other vertebrates. On a shorter time, scale, a fish usually adapts its physiological processes to meet the demands of a sudden change in water temperature. These physiological responses are usually directed toward meeting the increase in metabolic demand of the cells in response to the rise in temperature and stress. However, under chronic exposure to stress, a fish tends to acclimate itself by entering a state of metabolic depression and preserving energy reserves for the long haul. However, the effect of elevated or lower water temperature on fish metabolism (Q10 effect) is still not completely obliterated. Though the exact physiological pathways involved in the acclimation of fish to environmental changes are still unknown, the endocrine system response has a major role to play in regulating homeostasis and energy metabolism.

2 Stress Response in Fish

The general stress response in fish is categorized into primary, secondary, and tertiary responses (Barton 2002; Wendelaar Bonga 1997). The primary response refers to the neuroendocrine response in fish to the perception of stress. The release of catecholamines and corticosteroid hormones are the hallmark of primary stress responses that elicit alarm reactions. The catecholamines are released from the chromaffin tissues in the head kidney of the teleost and the adrenergic nerve endings (Faught et al. 2019; Wendelaar Bonga 1997). The interrenal tissue, in response to the pituitary hormones, such as the adrenocorticotrophic hormone (ACTH) secretes cortisol. The site of interrenal tissue is also the head kidney (Mommsen et al. 1999).

Since coping with stress is an energy-intensive process, the response of fish to primary stress hormones is to mobilize energy reserves, which results in increased blood glucose concentration through glycogenolysis and gluconeogenesis (Schreck and Tort 2016). In addition to energy metabolism, secondary stress response may also involve a change in hydromineral balance (Peter 2011). The tertiary stress response refers to the changes associated with the whole animal or population level after chronic exposure. The inability to cope with chronic stress may lead to detrimental effects such as reduced reproductive or foraging capacity. Chronic stress may also increase fish susceptibility to diseases. Fish stocks and populations may also leave the water bodies, where possible, to evade the stressful conditions.

3 Endocrine Response to Climate Change

The neuroendocrine response to stress, including that from climate change, is driven by simultaneous activation of (1) the sympathetic nervous system-chromaffin cell axis (SNC) and the (2) the hypothalamus–pituitary–interrenal (HPI) axis.

3.1 The Sympathetic Nervous System-Chromaffin Cell Axis

The chromaffin cells in the teleost, which is located in the head kidney, are the main source of circulating catecholamines in fish. The resting levels of catecholamines (epinephrine and norepinephrine) are usually below 5 nM in the teleost blood (Wendelaar Bonga 1997). However, under acute stress, the catecholamines increase immediately; epinephrine usually dominates. The catecholamines are also removed rapidly from the blood circulation. The cholinergic sympathetic nerves facilitate the calcium-mediated secretion of epinephrine from chromaffin cells (Reid et al. 1998). Furthermore, the catecholamine secretion has also been shown to occur due to noncholinergic stimulation, involving cortisol and adrenocorticotropic hormone (ACTH) (Reid et al., 1998; Wendelaar Bonga 1997).

Physiological Effects of the Catecholamines

The release of catecholamines in the blood initiates a stress response in fish characterized by higher ventilation rate, increased blood flow and oxygen diffusion capacity in the gills, and increased transportation of oxygen in the vascular system. The higher vascular catecholamines also have a stimulatory effect on cardiac output. Epinephrine released soon after stress also causes blood plasma acidification and cytoplasmic alkalinization, thus increasing the affinity of erythrocytes for blood (Nikinmaa 1992a, b). The catecholamines may also increase the blood hematocrit by stimulating erythropoiesis and causing the circulating erythrocytes to swell (Secombes et al. 1996; Wendelaar Bonga 1997).

A teleost under acute stress would not only require increased oxygen, but it would also need the energy to initiate an alarm reaction. Stress-induced hyperglycemia is commonly observed in fish (Barton and Iwama 1991; Hattingh 1977). The catecholamines stimulate hepatic glycogenolysis and release glycogen into the blood. Furthermore, catecholamines also induce the mobilization of free fatty acids in some fish (Mazeaud et al. 1977; Sánchez-Muros et al. 2013). Both glucose and free fatty acid can be used as substrates to meet the high energetic demands of coping with acute stress.

3.2 The Hypothalamic: Pituitary: Interrenal Axis

The pituitary acts as a connection between the brain and the peripheral endocrine system. The signals from the brain reach the pituitary and then the pituitary transmits the signal further to the endocrine glands in a manner that is specific for signal receptors. While the catecholamines are responsible for energy mobilization to meet the heightened demands of an alarm reaction, the cortisol redistributes the energy of an organism in a manner that facilitates the restoration of homeostasis for hours to days. This process is more precisely referred to as allostasis which is an adaptive process and refers to the establishment of homeostasis with the help of mediators such as cortisol (Galhardo and Oliveira 2009; Schreck and Tort 2016). The activation of the HPI axis and cortisol secretion thus lags the catecholamine response and can be used as an indicator of the stress response.

The site of cortisol/corticosteroid secretion is in the interrenal cells, which are also present in the head kidney. The endocrine control of cortisol in teleost is complex and still unclear. The secretion of corticotropin-releasing factor (CRF) from the hypothalamus stimulates the HPI axis, and the CRF stimulates the release of ACTH from the pituitary gland (Mommsen et al. 1999; Wendelaar Bonga 1997). Further, the studies suggest that the ACTH, which is a post-translational product of pituitary pro-opiomelanocortin (POMC), stimulates the interrenal cells to release cortisol (Wendelaar Bonga 1997).

Physiological Effects of Cortisol

Cortisol primarily acts on the gills, intestine, and liver to regulate hydromineral and energy balance in fish under stress (Faught et al. 2019; Faught and Vijayan 2016). Cortisol, through alteration of energy, can also affect growth, reproduction, and immune functions (Galhardo and Oliveira 2009; Wendelaar Bonga 1997). Climate change may result in osmoregulatory challenges to fish due to the increased melting of glaciers, altered precipitation, and increased evaporation in lakes. Under such conditions, cortisol assumes mineralocorticoid functions because of its stimulatory effects on branchial Na^+ and Cl^- excretory functions. The role of cortisol in the uptake of Na and Cl has also been established in fish (Laiz-carrión et al. 2003; McCormick et al. 2008).

4 Osmotic Stress Response

Fish that are exposed to osmotic stress constantly integrate signals from osmosensors and try to remodel their gill or gut epithelial to suit the magnitude, direction, and ionic composition of their blood and surrounding media (Kültz 2015; Takei and McCormick 2012). The calcium-sensing receptor (CaSR), transient receptor potential (TRP), cation channels, and voltage-gated Na^+ channels are some of the potential osmosensors in fish (Takei and Hwang 2016). Osmotic stress transcription factor (OSTF1) has been identified in a large number of fish, including Mozambique tilapia, black porgy (*Acanthopagrus schlegeli*), Nile tilapia (*Oreochromis niloticus*), and Japanese eel (*Anguilla japonica*) (see review by Kültz 2012). A change in the expression of mRNA is related to a change in the expression of Na^+/K^+ ATPase (NKA), NKCC transporter, and Na^+/H^+ proteins (Tse et al. 2007). Since remodeling of osmoregulatory structure and associated transporters is energy-intensive, it is suggested that the release of catecholamines could aid this and increase the perfusion of the gills to meet increased aerobic demand. However, the increased perfusion of the gills could also lead to increased branchial permeability to ions and water, a metabolic compromise to meet the immediate energy demands of fish under stress (Wood and Eom 2021). Cortisol is also known to directly influence osmoregulation in fish by stimulating branchial NKA and chloride cells (McCormick 2001). In freshwater fish, cortisol has been implicated to promote ion uptake through apical Na^+/H^+ exchanger (NHE), vacuolar-type H^+-ATPase (VHA), Na^+/Cl^- cotransporter (NCC), epithelial Ca^+ channel (ECaC), and basolateral NKA (Kwong et al. 2016). Remodeling of tissue structure and cytoprotection from unfavorable environmental salinity would also require protein stabilizers and chaperons. Hence heat shock proteins can also play an important role in acclimation to environmental stress.

5 Role of Heat Shock Proteins

The heat shock proteins (HSP) are chaperon molecules that maintain cellular protein homeostasis and constitute an essential component of the cellular stress response mechanism. Stressors, such as thermal and osmotic shock, can lead to structural instability of cellular proteins, thus induction of HSPs helps in maintaining the protein structural conformation (Mohanty et al. 2018). The HSP70 isoform is one of the most studied heat shock proteins in response to environmental stressors. The regulation of HSP occurs through the activation of heat shock factors (HSF) through their interaction with the promoter region of the heat shock genes. Among various forms of HSF, the HSF1 is considered the most important in regulating the HSP in response to stressors. The HSF1 is usually present in a latent monomeric form, bound to the HSP70 in the cytoplasm. However, upon detection of non-native (misfolded) proteins due to stress, the HSP-HSF1 bond is ubiquitinated. As a consequence, the HSF1 is now set free and it oligomerizes to form a trimer, which is translocated to the nucleus. In the nucleus, the HSF1 is phosphorylated at its serine residues, making it ready to bind at the promoter region (heat shock elements; HSE) that is located upstream of the *HSP* genes (Gomez-Pastor et al. 2018; Santoro 2000). This results in a stress response.

The heat shock response has been studied in a large number of fish (Dawood et al. 2020; Mohanty et al. 2018; Sales et al. 2019). The heat shock response is energetically expensive and could account for more than 50% of the energy budget of the cell (Houlihan 1991), which signifies the importance of heat shock proteins in combating environmental stress and the role of cortisol (Iwama et al. 1999). It was demonstrated that cortisol could reduce *de novo* synthesis of HSP70 in post-stress rainbow trout hepatocytes (Boone and Vijayan 2002). In contrast, the constitutive form of HSP70 (performs housekeeping functions) in the rainbow trout livers is increased due to cortisol treatment, thus contributing to increased stress tolerance capacity (Vijayan et al. 2003). Thus, it is possible that exposure to multiple bouts of stress and secretion of cortisol could increase stress tolerance in fish (cross-protection). Although the reduced expression of the inducible form of HSP70 under stress is perhaps a mechanism of conserving energy since the heat shock reaction requires a lot of energy expenditure.

6 Conclusion

The general stress response in fish can be categorized into primary, secondary, and tertiary responses. The primary responsibility involves catecholamines and cortisol to elicit an alarm reaction. The catecholamines and cortisol are released from the chromaffin and the interrenal tissue of the head kidney. The role of the primary stress hormones is to mobilize energy reserves to meet the requirements of the alarm response of fish. In addition to energy metabolism, secondary stress response may also involve a change in hydromineral balance. Immediately after the perception of the stress response, the catecholamines in the blood increase ventilation rate, blood flow, and oxygen diffusion capacity in the gills. This is to facilitate aerobic respiration to meet the high energy demands. The higher vascular catecholamines also have a stimulatory effect on cardiac output. Cortisol is a hormone with multiple physiological roles such as regulating energy, facilitation of hydromineral balance, and myriad other cellular homeostatic functions to help fish adapt to most abiotic challenges that a fish might experience because of climate change.

References

Barton BA (2002) Stress in fishes: a diversity of responses with particular reference to changes in circulating corticosteroids. Integr Comp Biol 42(3):517–525. https://doi.org/10.1093/icb/42.3.517

Barton B, Iwama G (1991) Physiological changes in fish from stress in aquaculture with emphasis on the response and effects of corticosteroids. Annu Rev Fish Dis 1(C):3–26

Boone AN, Vijayan MM (2002) Glucocorticoid-mediated attenuation of the hsp70 response in trout hepatocytes involves the proteasome. Am J Physiol Regul Integr Comp Physiol 283:R680–R687. https://doi.org/10.1152/ajpregu.00125.2002

Dawood MA, Eweedah NM, Elbialy ZI, Abdelhamid AI (2020) Dietary sodium butyrate ameliorated the blood stress biomarkers, heat shock proteins, and immune response of Nile tilapia (Oreochromis niloticus) exposed to heat stress. J Therm Biol 88:102500

Faught E, Vijayan MM (2016) Mechanisms of cortisol action in fish hepatocytes. Comp Biochem Physiol B Biochem Mol Biol 199:136–145. https://doi.org/10.1016/j.cbpb.2016.06.012

Faught E, Hernandez-Perez J, Wilson JM, Vijayan MM (2019) Stress in response to environmental changes. In: Climate change and non-infectious fish disorders

Galhardo MLS, Oliveira RF (2009) Psychological stress and welfare in fish. ARBS Ann Rev Biomed Sci 11:1–20. https://doi.org/10.5016/1806-8774.2009v11p1

Gomez-Pastor R, Burchfiel ET, Thiele DJ (2018) Regulation of heat shock transcription factors and their roles in physiology and disease. Nat Rev Mol Cell Biol 19:4–19. https://doi.org/10.1038/nrm.2017.73

Hattingh J (1977) Blood sugar as an indicator of stress in the freshwater fish, *Labeo capensis* (Smith). J Fish Biol 10(2):191–195

Houlihan D (1991) Protein turnover in ectotherms and its relationships to energetics. In: Advances in comparative and environmental physiology. Springer, pp 1–43

IPCC (2022) Climate change 2022: impacts, adaptation, and vulnerability. In: Pörtner H-O, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds) Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Iwama GK, Vijayan MM, Forsyth RB, Ackerman PA (1999) Heat shock proteins and physiological stress in Fish1. Am Zool 39:901–909. https://doi.org/10.1093/icb/39.6.901

Kültz D (2012) The combinatorial nature of osmosensing in fishes. Physiology 27:259–275

Kültz D (2015) Physiological mechanisms used by fish to cope with salinity stress. J Exp Biol 218: 1907–1914

Kwong RW, Kumai Y, Tzaneva V, Azzi E, Hochhold N, Robertson C, Pelster B, Perry SF (2016) Inhibition of calcium uptake during hypoxia in developing zebrafish is mediated by hypoxia-inducible factor. J Exp Biol 219:3988–3995

Laiz-carrión R, Martín Del Río MP, Miguez JM, Mancera JM, Soengas JL (2003) Influence of cortisol on osmoregulation and energy metabolism in gilthead seabream Sparus aurata. J Exp Zool A Comp Exp Biol 298A:105–118. https://doi.org/10.1002/jez.a.10256

Mazeaud MM, Mazeaud F, Donaldson EM (1977) Primary and secondary effects of stress in fish: some new data with a general review. Trans Am Fish Soc 106:201–212. https://doi.org/10.1577/1548-8659(1977)106<201:PASEOS>2.0.CO;2

McCormick SD (2001) Endocrine control of osmoregulation in teleost fish. Am Zool 41:781–794. https://doi.org/10.1093/icb/41.4.781

McCormick SD, Regish A, O'Dea MF, Shrimpton JM (2008) Are we missing a mineralocorticoid in teleost fish? Effects of cortisol, deoxycorticosterone and aldosterone on osmoregulation, gill Na^+, K^+-ATPase activity and isoform mRNA levels in Atlantic salmon. Gen Comp Endocrinol 157:35–40. https://doi.org/10.1016/J.YGCEN.2008.03.024

Mohanty BP, Mahanty A, Mitra T, Parija SC, Mohanty S (2018) Heat shock proteins in stress in Teleosts. In: Asea AAA, Kaur P (eds) Regulation of heat shock protein responses, heat shock proteins. Springer International Publishing, Cham, pp 71–94. https://doi.org/10.1007/978-3-319-74715-6_4

Mommsen TP, Vijayan MM, Moon TW (1999) Cortisol in teleosts: dynamics, mechanisms of action, and metabolic regulation. Rev Fish Biol Fish 9:211–268. https://doi.org/10.1023/A:1008924418720

Nikinmaa M (1992a) How does environmental pollution affect red cell function in fish? Aquat Toxicol 22:227–238

Nikinmaa M (1992b) Membrane transport and control of hemoglobin-oxygen affinity in nucleated erythrocytes. Physiol Rev 72(2):301–321

Peter M (2011) The role of thyroid hormones in stress response of fish. Gen Comp Endocrinol 172 (2):198–210

Reid S, Bernier N, Perry S (1998) The adrenergic stress response in fish: control of catecholamine storage and release. Comp Biochem Physiol C: Pharmacol Toxicol Endocrinol 120:1–27

Sales CF, Lemos FS, Morais RD, Thomé RG, Santos HB, Pinheiro AP, Bazzoli N, Rizzo E (2019) Thermal stress induces heat shock protein 70 and apoptosis during embryo development in a Neotropical freshwater fish. Reprod Fertil Dev 31:547–556

Sánchez-Muros MJ, Villacreces S, Miranda-de la Lama G, de Haro C, García-Barroso F (2013) Effects of chemical and handling exposure on fatty acids, oxidative stress and morphological welfare indicators in gilt-head sea bream (Sparus aurata). Fish Physiol Biochem 39:581–591. https://doi.org/10.1007/s10695-012-9721-2

Santoro MG (2000) Heat shock factors and the control of the stress response. Biochem Pharmacol 59:55–63. https://doi.org/10.1016/S0006-2952(99)00299-3

Schreck CB, Tort L (2016) The concept of stress in fish. Fish Physiol 35:1–34. https://doi.org/10.1016/B978-0-12-802728-8.00001-1

Secombes C, Hardie L, Daniels G (1996) Cytokines in fish: an update. Fish Shellfish Immunol 3 (4):291–304

Takei Y, Hwang P-P (2016) Homeostatic responses to osmotic stress. In: Fish physiology. Elsevier, pp 207–249

Takei Y, McCormick SD (2012) Hormonal control of fish euryhalinity. In: McCormick SD, Farrell AP, Brauner CJ (eds) Fish physiology. Academic Press, Cambridge, pp 69–123. https://doi.org/10.1016/B978-0-12-396951-4.00003-7

Tse WK, Au DW, Wong CK (2007) Effect of osmotic shrinkage and hormones on the expression of Na+/H+ exchanger-1, Na+/K+/2Cl–cotransporter and Na+/K+-ATPase in gill pavement cells of freshwater adapted Japanese eel, Anguilla japonica. J Exp Biol 210:2113–2120

Vijayan MM, Raptis S, Sathiyaa R (2003) Cortisol treatment affects glucocorticoid receptor and glucocorticoid-responsive genes in the liver of rainbow trout. Gen Comp Endocrinol 132:256–263

Wendelaar Bonga SE (1997) The stress response in fish. Physiol Rev 77:591–625

Wood CM, Eom J (2021) The osmorespiratory compromise in the fish gill. Comp Biochem Physiol A Mol Integr Physiol 254:110895. https://doi.org/10.1016/j.cbpa.2021.110895

Impact of Climate Change on Emergence of Biotoxin in Fish and Shellfish

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Abstract

Biotoxins in aquatic ecosystem have major implications in both aquatic and human health. More than 100 known species of marine algae are harmful. Major 5 groups of biotoxins have been classified till date but the advent of climate change across globe results in various changes in their type and congeners. Several biotic and abiotic factors along with coastal eutrophication and seasonal upwelling enhance the blooming of HABs, due to the abundance of high nutrient contents along with regional warming. HABs are responsible for the production of biotoxins via consumption contaminated bivalve mollusks (PSP and DSP) and large predatory reef fishes (ciguatoxin). This opens up immense research opportunities in the characterization of the toxin produced by the HABs. Several reports are available suggesting that HABs are spatially and temporally distributed causing morbidity and death in marine organisms. Analysis of biotoxins has been up trended with latest technologies but still MBA remains legal as per regulatory guidelines. This chapter aims to focus on different types of biotoxins produced, several factors affecting its emergence in aquatic ecosystems due to climate change and their analysis.

Keywords

Fish and shellfish · Biotoxins · Climate change · Analysis

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1 Introduction

Biotoxins are associated with the growth and multiplication of certain phytoplankton called harmful algal blooms. Among 5000 known marine algae, more than 100 species are known to produce toxins which are harmful for living organisms (Vargo 2009). Biotoxins of both marine and freshwater origin are reported to occur across the world in different climatic conditions. The consumption of biotoxins via eating toxin containing seafood, direct contact with contaminated sources like water or food results in poisoning in human being. The biotoxins enter in to bivalve mollusk and get accumulated in these organisms due to its filter feeding habits. Predatory fishes and bivalve mollusks have been reported with different kind of marine toxins. Fishes at the higher food web accumulate biotoxins in their body by consuming herbivorous fishes and bivalves being filter feeders usually accumulate poison by feeding on toxic algae.

Several incidences of sea life disruption due to biotoxin formation have been reported and are increasingly responsible for human intoxication in the twenty-first century. The coloured algal blooms occurs in red tides are known to contain poisonous compounds which get into the food system, and harm human as well as animals. Many a time green algal blooms happen in the ocean but that is not toxic to water inhabitants and their consumers. Harmful algal blooms (HABs) disrupt whole aquatic ecosystem periodically. Several incidences of poisoning have been reported with red tide. It is always advisable not to harvest fish and shellfish from the area where HABs are detected. HABs generally occur in vast areas, when the conditions of temperature, salinity, nutrient, sunlight, and tidal environments are coinciding with the favorable growth conditions of marine algae. In few instances, HABs are highly localized and are found near to damaged coral reef, cyclone reported area, etc. (Moy and Todd 2014).

Biotoxins are toxic at extremely low doses to human and they are considered to be environmental contaminants (Paterson 2006). The human health effects due to the exposure to biotoxins vary from bacterial intoxication and infections (Jain et al. 2014). Symptoms related to seafood poisoning are dependent on the toxin produced by the associated marine algae (ECDC 2022). Five major types of poisoning are associated with shellfish consumption in human. They are paralytic shellfish poisoning (PSP), diarrheic shellfish poisoning (DSP), amnesic shellfish poisoning (ASP), neurotoxic shellfish poisoning (NSP), and azaspiracid shellfish poisoning (AZP). In addition to these, there are two types of poisoning associated with the consumption of fin fishes. They are ciguatera fish poisoning and pufferfish poisoning (Ababouch 2014). Climate change is a major factor in marine ecosystem which is responsible to cause ecological imbalance in several abiotic and biotic factors and thus resulting negative impacts on the health of the biological organisms as well as human. Effective regulatory and institutional strategies are required to mitigate this invisible hazard (Bauer 2006).

2 Classification

In world, toxic marine algae belong to dinoflagellates (54 species), diatoms (17species), dictyochophytes (3 species), haptophytes (6 species) and raphidophytes (4 species) (Zingone et al. 2021). The large and diverse group of algae resulted in different categories (Hinder et al. 2011). Marine biotoxins can be distinguished as either water or fat-soluble. The water soluble biotoxins include ASP and PSP and pufferfish poisoning (PFP). The lipid soluble toxin includes DSP, AZP, ciguatera fish poisoning (CFP) and NSP (Visciano et al. 2016). As per the known chemical structure of marine biotoxins, they have been classified into azaspiracid, brevetoxin, cyclic imine, domoic acid, okadaic acid, pectenotoxin, saxitoxin and yessotoxin groups. In addition to these, palytoxin and ciguatoxin have also been identified (EFSA 2009a). Biotoxins are also odorless, colorless and tasteless (Khan et al. 2001). Effective regulatory and institutional strategies are necessary to mitigate this invisible hazard (Bauer 2006). HABs derived biotoxin forms health concern in aquatic organisms such as fish, shellfishes, seabirds, marine mammals, etc., in which caged fish and shellfishes are more prone to fatality. The regulatory agencies for food safety have provided limits for biotoxin to safeguard human health (Table 1).

3 Biotoxin Properties

3.1 Paralytic Shellfish Poisoning

Paralytic shellfish poisoning is due to the consumption of shellfish contaminated with one or more saxitoxins, saxitoxin derivatives or related toxins of saxitoxins. These toxins are produced by harmful algal blooms of dinoflagellate category mainly *Alexandrium, Gymnodinium*, *Pyrodinium* species and are considered as one of the most potent biotoxin reported across the world. The toxicity of saxitoxin is greatly influenced due to the presence of several STX derivatives. Paralytic shellfish toxins have been reported in several cases of mortalities and morbidities and muscular paralysis have been reported in outbreaks. The illness is characterized by the fast onset of neurological symptoms shortly after the consumption of contaminated shellfish (30 min to 2 h). The major symptoms are fever, rash, numbness, tingling, burning, drowsiness, etc. In later period of time, after 24 h of consumption, respiratory severity and other complications such as paralysis and death may occur (Klöpper et al. 2003; Leikin and Paloucek 1998). These toxins are generally tetrahydropurine compounds of either carbamate, dicarbamoyl, N-sulfo carbamoyl or deoxy decarboamoyl compounds. Saxitoxins and gonyautoxins (1–4) are grouped under carbamate group. These toxins are generally heat stable at acidic pH; however, the stability will be lost and easily broken-down or oxidized at higher pH. Among the different group of toxins, N-sulfo carbamoyl compounds are unstable to heat even at acidic pH. Saxitoxin possesses two guanidine compounds to tetrahydropurine compound (3,4-propinoper hydropurine tricyclic compound) which provides hydrophilic nature to it (Shimizu 2000). M-series toxins are the

Table 1 Different classes of marine biotoxins and their regulatory limits

Group	Marine biotoxin	Source	Regulatory limits			Clinical symptoms
			FSSAI	USFDA	EU	
PSP	Saxitoxin	Dinoflagellates (*Alexandrium* spp.; *Gymnodinium catenatum*; *Pyrodinium bahamense*)	80 µg per100 g in Bivalves	80 µg per 100 g in all fish	800 µg per kg	• Gastrointestinal problems • Paralytic attacks • Lethal
ASP	Domoic acid	Diatoms (*Pseudonitzschia* spp.; *Nitzschia* spp.; *Nitzschia australis*)	20 µg per g in Bivalves	≥20–30 mg per kg in all fish	20 mg per kg	• Gastrointestinal and neurological problems • Cardiac or respiratory problems • Lethal
DSP	Okadaic acid	*Prorocentrum lima*; *Dinophysis* spp.	160 µg/kg in Bivalves	≥ 0.16 mg per kg	160 mg per kg in live Bivalve	• Gastrointestinal problems• Non-lethal
NSP	Brevetoxin	Karenia brevis *Gymnodinium* spp. and *Heterosigma* spp.	200 MU or equivalent/kg in Bivalve	≥0.8 mg per kg = 20 MU per100 g in mollusks	–	• Gastrointestinal and neurological problems • Respiratory problems • Lethal
CFP	Ciguatoxin	Dinoflagellates (*Gambierdiscus* spp.; *Prorocentrum* spp., *Ostreopsis* spp. including *Coolia monotis*, *Thecadinium* and *Amphidinium carterae*)	–	Caribbean ciguatoxin-1: ≥0.1 µg/kg (C-CTX) Indian ciguatoxins: Not specified • Pacific ciguatoxin-1: ≥0.01 µg/kg (P-CTX-1)	–	• Gastrointestinal symptoms • Cardiovascular or neurological problems
	Pectenotoxin	*Dinophysis* spp.	–	–	–	• Gastrointestinal symptoms

	Yessotoxin	*Protoceratium reticulatum* *Lingulodinium polyedrum* *Gonyaulax spinifera*	–	–	1 mg of yessotoxin equivalent per kg m	• Low availability of data in humans
	Azaspiracid	*Amphidoma languida* *Azadinium spinosum*	160 μg of azaspiracid equivalent/kg Bivalve Mollusks	≥0.16 mg/kg azaspiracid-1 equivalents (i.e. combined azaspiracid-1, 2 and -3).	160 μg of azaspiracid equivalents per kg	• Gastrointestinal problems
	Cyclic imine	*Alexandrium* spp.; *Karenia* spp.	–	–	–	• Low availability of data in humans
	Palytoxin	*Palythoa* spp.; *Ostreopsis* spp.	–	–	–	• Gastrointestinal, muscular and cutaneous problems

Source: Visciano et al. (2016), Suresh et al. (2014), Villalobos et al. (2015), Mackenzie et al. (1995), Haywood (1998); https://www.fssai.gov.in/upload/uploadfiles/files/Compendium_Contaminants_Regulations_28_01_2022.pdf; https://www.fda.gov/media/80400/download; https://www.eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02004R0853-20100715& from=EL new STXs analogues proposed very recently (Leal and Cristiano 2022). STX is soluble only in polar solvents such as methanol with high solubility, whereas in ethanol and glacial acetic acid it shows less solubility (Schantz et al. 1961).

3.2 Amnesic Shellfish Poisoning (ASP)

The amnesic shellfish poisoning is due to the consumption of shellfish containing toxin, called domoic acid (Wright et al. 1989). The illness is characterized by both gastrointestinal and neurological disorders and causes death in fatal cases. Both gastrointestinal (vomiting, fever, abdominal pain) and neurological symptoms (dizziness, headache, memory loss, respiratory complications) may appear shortly after the consumption of contaminated shellfish, usually within 24–48 h of ingestion (Suresh et al. 2014). The main source of domoic acid accumulation has been reported from viscera of contaminated shellfish. The toxin is one of the potent naturally occurring neurotoxins and structurally it belongs to kainiod group. This class of compound acts as neurotransmitter, which binds specific receptor protein of neuron. This compound aided in cell damage through neuronal depolarization. The toxin domoic acid is water soluble, crystalline in nature, and categorized as an acidic amino acid. The isomeric forms of domoic acid include isodomoic acid A-F, C5'diastereomer and domomilactones (Wright and Quilliam 1995; Ravn 1995).

3.3 Diarrhetic Shellfish Poisoning (DSP)

Several species of dinoflagellates, mainly Dinophysis and *Prorocentrum* are known to produce lipophilic toxin called okadaic acid which causes DSP in humans. The illness is characterized with gastrointestinal symptoms such as diarrhea, vomiting, fever, abdominal pain, etc. within few minutes of consuming contaminated shellfish. The toxin is heat stable and does not affect the culinary and organoleptic properties of seafood. Usually illness due to this toxin is not fatal and patients get recovered with or without medical assistance (Climent et al. 2001; Currie 2000). The toxins of DSP are all heat stable polyether and lipophilic compounds (Draisci et al. 1996).

3.4 Neurotoxic Shellfish Poisoning (NSP)

Neurotoxic shellfish poisoning is due to the consumption of shellfish containing lipophilic toxin called brevetoxin. These toxins are produced by dinoflagellate, *Gymnodinium breve* (or *Ptychodiscus brevis*). The toxin is cyclic polyether and a potent neurotoxin. Like other shellfish toxins, these are also heat and acid stable. Brevetoxins is the causative agent for NSP. The NSP toxins, called brevetoxins, are tasteless, heat and acid stabile, lipid soluble, cyclic polyether neurotoxins produced by the marine dinoflagellate such as *G. breve* (or *Ptychodiscus brevis*). Brevetoxin has two distinct types based on the backbone structures as Type A and Type B and has 10–11 transfused rings. The head and tail portions of both types have similar functional elements such as lactone moiety, unsaturated alpha and beta aldehyde sidechain, etc. (Benson et al. 1999). These brevetoxins have the affinity to bind with voltage sensitive sodium channel on its 5′ end, thereby initiating the toxic properties (Cembella et al. 1995). The intoxication symptoms of both NSP and CFP are found similar in nature especially both gastrointestinal and neurological illness. However, the illness of NSP is less severe compared to CFP and no death has been reported so far and fast recovery within few days has been noted (Rafuse et al. 2004; Schnorf et al. 2002).

3.5 Ciguatera Fish Poisoning (CFP)

Ciguatera poisoning is due to the consumption of toxin contaminated reef fishes. Ciguatoxin or maitotoxin is responsible for foodborne outbreaks and it is produced by dinoflagellate *Gambierdiscus* species which are predominantly found in reef areas. The herbivorous fishes accumulate these toxins while gazing the toxic dinoflagellates and are subsequently bioaccumulated on higher food web levels. Ciguatera fish poisoning occurs when human consumes the carnivorous fishes such as coral trout, snapper, grouper, etc. in the tropical and subtropical regions (Klöpper et al. 2003; Kim et al. 1999). CFP results in gastrointestinal (diarrhea, vomiting and abdominal pain) symptoms during the onset of disease, followed by neurological (muscular pain, dizziness, numbness, tingling, etc.) and cardiovascular (paralysis and respiratory disorders) symptoms. Recovery time is unpredictable and varies from few weeks to years. Mannitol treatment during the onset of illness has been reported to cure the symptoms drastically. Ciguatoxin is considered as one of the potent neurotoxins and ingestion of as low as 0.08 μg/kg poses severe health risk to human. The toxicity is due to its specific binding to voltage dependent sodium channel and thereby losing cell permeability which eventually leads to the onset of illness in human. No antidote is available to cure the disease. The supportive therapy depending upon the symptoms is advisable. Complete prevention of illness is only by avoiding the consumption of contaminated reef fishes and not to harvest from ciguatoxin contained area. Presently, there are no methods available for the routine checking of ciguatoxin level in seafood meant for human consumption. This toxin is usually found in Pacific, Caribbean Sea and Indian oceans and about 400 species of fishes are known to be the vectors of this illness (Lehane and Lewis 2000; Lehane 2000; De Fouw et al. 1999). Ciguatoxins are lipophilic, ladder like polyether compounds comprising 13 to 14 ether linked rings. The toxin is stable to heating, cooking and freezing.

3.6 Azaspiracid Shellfish Poisoning

Azaspiracid shellfish poisoning is an emerging class of algal toxin caused by the consumption of shellfishes especially mussels when it contaminated with dinoflagellate *Protoperidinium crassipes and Azadinium spinosum.* AZP toxins or azaspiracids (formally known as “Killary-toxin” or KT-3) are lipophilic, polyether amino acid toxins which cause severe gastrointestinal disorders (Twiner et al. 2008; Satake et al. 1998). The toxin is cytotoxic in nature and is found to inhibit or block the calcium channel. The illness is first reported in Netherland in 1995 and identified as a causative agent for seafood borne outbreak in eight individuals who had bivalve mollusk, *Mytilus edulis.* The symptoms are similar to diarrhetic shellfish poisoning (DSP) toxins (Tillmann et al. 2016; Turner and Goya 2015).

4 Prevalence of Marine Biotoxins

The harmful algal blooms have become more prevalent owing to climate change (global warming), eutrophication and anthropogenic pressures (Visciano et al. 2016). Certainly with this, occurrence of marine biotoxins and consequently, risk to public health has increased. The consumption of foods associated with these biotoxins can cause severe health complications. As per EU one health zoonoses report 2020, there were 23 outbreaks of biotoxins, out of which 1 was classified as strong-evidence outbreak. And, these outbreaks caused 120 cases of illness which led to 6 hospitalizations. The outbreaks were reported from Cyprus, France, Netherlands and Spain. Ciguatoxin was identified as the causative agent in 9 outbreaks (Varela Martínez et al. 2021). Paralytic shellfish poisoning was first reported in Tamil Nadu state in 1981 when 82 serious cases, including three deaths, were reported after a history of oyster consumption (CMFRI 2011). More than 2000 cases of paralytic shellfish poisoning reported mortality of 15% globally per year. In developing countries, its burden may have been underestimated. In Tamil Nadu state of India, two shellfish poisoning cases were reported in 2015 due to consumption of clam *Meretrix meretrix*, although the presence of toxin was not analyzed (Velayudhan et al. 2021). During 2011–2015, biotoxin remained most frequently occurring hazard (14.8%) in bivalve mollusks after pathogenic micro-organisms (65.1%). Among the biotoxin cases most were due to the presence of diarrhoeic shellfish poisoning (DSP) toxins (63%), followed by paralytic shellfish poisoning (PSP) toxins (14%), amnesic shellfish poisoning (ASP) toxins (11%), yessotoxin (YTX) (6%) and azaspiracid shellfish poisoning (AZP) toxins (6%). This non-compliance was observed from EU member states notably, Spain (21.5%), France (16.9%), Italy (16.9%) and the UK (16.9%). As per FAO (2020), a total of 52 consignment of seafood were found with different marine biotoxins such as DSP, ASP, PSP and ciguatoxin in the period of 2016 to 2021.

5 Climate Change and Occurrence of Biotoxins

Coastal zones support the growth of wide variety of aquatic organisms as these productive areas have abundant nutrients from land run off, topographical structures and water retention properties. The coastal zones are mostly influenced by manmade activities and temperature variations in comparison to open waters. Several anthropogenic activities, agricultural and municipal run off result in the excessive accumulation of nutrients in the coastal water that favors the growth of algal blooms. Profuse growth of algal blooms results in reduction in total dissolved oxygen content of the system leading to hypoxia. Optimum nutrient and environmental parameters like temperature, salinity, tidal amplitude, oxygen and CO_2 concentration favour bloom proliferation in marine environment. The favorable period of HABs in temperate waters lies on late spring and early summer seasons where the temperature became warm and sufficient for the stratification of oxygenated surface and hypoxic bottom waters. The climate change due to global warming and several anthropogenic activities has resulted in higher occurrence of HABs in marine waters. The major changes in the climate include rise in seawater temperature, hypoxic stress, increased acidity, hardness and calcification which hampers the major biological functions of ecosystem. Major impacts of climate change comprise variations in species distribution and changes in their habitats, physiological, metabolical and reproductive functions along with resulting stress to adapt to changed environmental conditions. Climate changes have led to increase of disease outbreaks with rise in the occurrence of environmental contaminants, pesticides, antibiotic residues, etc. and deadly diseases in terrestrial populations. Aquatic ecosystems may be the worst affected due to intense climatic changes.

6 Effect of Climatic Conditions and Emergence of Biotoxins

Global warming had profound influence on the growth of phytoplankton as increase in temperature potentiates the physiological process to a greater extent and seasonal abundance of certain harmful algal blooms and the expansion of growth to nearby geographical conditions have been reported (Moore et al. 2009). Global warming increases the stratification and supresses the nutrient mixing between upper and deeper waters and active photosynthesis remains at the upper stratified water column leaving depletion of nutrients in the deeper waters. This strategic condition enhances the growth of harmful algae and utilizes all available nutrients, trace metals and other macronutrients and spreads to other area where nutrients are available. Coastal eutrophication resulted from anthropogenic activities is the major factor for the blooming of HABs. Vertical migration of HABs from surface waters to bottom waters during night has been reported and benthic animals have also been affected with biotoxin exposure. In addition to coastal eutrophication, the seasonal upwelling also promoted the blooming of HABs, due to the abundance of high nutrient contents along with regional warming. The blooming of HABs leads to the development of hypoxic conditions leading to the mass mortality of other marine organisms. Largest HABs so far recorded due to seasonal upwelling and warming of surface temperature are *Pseudonitzschia australis* blooms of west coast of USA and the biotoxin called domoic acid from this bloom resulted in mass mortality of marine animals including seabirds, whales, fish, etc. The several stress factors such as low oxygen content, HABs, rise tin temperature are the major factors which intensified domoic acid exposure. The effect of temperature on growth and toxin productions of HABs is scanty and no definite relationship exists till date. Warmer temperature promotes the growth of certain HABs like *Dinopysis* spp. responsible to increased DSP concentration. This is reverse for *Alexandrium* spp. which grows less in warmer temperature. It has been reported that high concentration of carbon dioxide favors the growth and toxin production in *Alexandrium* spp., *Karlodinium venefecum* and *P. mutliseries* in which a species and strain dependent differences also reported among these species. Similarly, high pH has the positive impact on growth of HABs; however, the higher growth rate and toxin production have been noticed in high CO_2 and low pH condition suggesting that excess carbon might be the reason for enhanced growth rate and toxin production in HABs.

As per Intergovernmental Panel on Climate Change (IPCC, Switzerland), no direct relationship exists between the presence of an algal bloom and poisoning outbreak in world. Human poisoning can even occur in the absence of algal bloom. PSP and DSP are two main types of biotoxin poisoning which have been reported to be associated with temperate of the coastal water and climatic condition of the region. Biotoxins such as ciguatera have been reported mostly from warmer waters, i.e. tropical waters.

7 Emergence of Biotoxin Derivatives

Fish and shellfishes have been associated with biotoxin poisoning which bioaccumulates the toxins by grazing or filter feeding on dinoflagellates or diatoms and hence toxins get into the tissues. In some cases toxins are metabolized in the shellfishes and found to be more potent derivatives of the precursor molecules of that toxin. Various classes and different congeners within a particular class of toxin existence complicate analysis as well as monitoring.

The existence of multiple toxin classes and multiple congeners within a given class complicates monitoring and analysis. Hence, the mouse bioassay (MBA) is still acceptable for testing of biotoxin by regulatory bodies as this assay is able to detect total composite toxicity. Most of biotoxins are heat stable which cannot be degraded by any thermal processing method. In case of saxitoxin, heat processing increases the toxicity by converting mild toxic derivatives to more toxic forms. Hence source control is very important to control biotoxins instead of any food processing methods.

Special skill and high cost equipment are major disadvantages that inhibit regular monitoring of toxicity in fish and shellfish. So the MBA is adopted for continuous monitoring of algal bloom toxicity and foods.

With the increasing availability of advanced instrumentation, such as mass spectrometry, paired with observations by electron microscopy, there have been numerous discoveries of new toxic algal species and novel toxins and derivatives. Additionally, well-studied toxins such as PSP appear to be expanding in range and some suggest that ballast discharge from international shipping and climate change is at least partially responsible for expansion in the geographical ranges of some toxic algal species. M-series toxins are the new STXs analogues proposed very recently (Leal and Cristiano 2022).

8 Analysis of Biotoxins

Marine biotoxins responsible for human health threats comprises individual or group of structurally related compounds which are known to be congeners having different potencies (Van Dolah and Ramsdell 2001; Suresh et al. 2014). Toxin analysis can be categorized into three types as in vitro, in vivo and chemical assays (Hallegraeff et al. 2003). Mouse bioassay (MBA) is an acceptable method as per European Food Safety legislation for Official Control testing for PSP and DSP in which mice is used as a model to study the toxicity of the test material via injecting the extract into mice for any symptoms of illness (Environment, Food and Rural Affairs: Fifth Report. Session 2003/04. House of Commons. [http://www.publications.parliament.uk]; Yasumoto et al. 1978). The MBA method seems to have ethical objections that lead to find alternative approaches for biotoxin detection (Morris et al. 2007a, b; Chapela et al. 2008). Commission regulation (EC) No. 2074/2005 allows other detection method, as a substitute method to the MBAs, for the determination of toxicity as long as EC 853/2004 valid (EFSA 2010). High throughput instruments are used in chemical methods for the analysis of biotoxin and high-performance liquid chromatography (HPLC), liquid chromatography-mass spectrometry, LC–MS/MS, etc. are commonly used for chemical assays (Quilliam 1996). High-performance liquid chromatography (HPLC) methods have been in use since 2006 as a qualitative test method along with MBA for the determination of marine biotoxins (Turrell et al. 2007). Presently, the biotoxin determination (including various marine toxins and its derivatives) is carried out by liquid chromatography-mass spectrometry (LC–MS) and liquid chromatography UV detection (LC-UV) (EFSA 2009a, b; Magdalena et al. 2003; Ofuji et al. 1999; Christian and Luckas 2008). Among the in vitro assays, functional assays such as cytotoxicity assays, enzyme inhibition assays, receptor binding assays have been used as in vitro methods for the detection of marine biotoxins (Manger et al. 1995; Della et al. 1999; Van Dolah et al. 1994). The functional assays are structural assays in which the test results are interpreted based on the interaction of toxin with receptor cells and possible structural or conformational changes in the cells are able to conclude the presence of the toxin in the test sample. Hence the use of automation is one of the advantages in structural assays compared to in vivo studies. Several assays based on antigen antibody reactions have been developed for various biotoxins and are widely used for testing (Laycock et al. 2001; Cembella et al. 2003). Onsite testing or field level testing kits are available based on immunoassays and one of the such assay uses the property of surface plasmon resonance (SPR for onsite testing and quantification of toxin levels in water as well as in seafoods) (Stevens et al. 2007). In addition to these, presently screen-printed electrodes are also used for in situ studies due to its accurate and sensitive determination of biotoxins in the sample (SPEs; Kreuzer et al. 2002; Micheli et al. 2004). Screen-printed electrodes have been successfully used for the detection of several toxins such as brevetoxin, domoic acid, okadaic acid, etc. and the simplicity in use, design and handling makes them a good candidate of choice for in vitro studies. The major limitations in toxin analysis is the lack of reference materials or standards and lack of knowledge on the potency of equivalent toxic substitutes. So further development in this direction will help to lessen the analysis risk to a greater extent.

9 Mitigation for Biotoxins

Knowledge of fish or shellfish origin, environmental status of the harvesting area, regular monitoring and surveillances may be the key factor for control of biotoxins intoxication to human being. Fishing areas should primarily be notified/de-notified on proactive basis to check incidences of the food poisoning due to biotoxins. The food processors should be actively involved for establishing a robust system for product traceability as well as recall procedure. The consumption of large predatory reef fishes should be avoided. PSP is prevented by large-scale proactive monitoring programs for toxins in shellfishes harvest areas. Analytical capabilities of laboratories for biotoxins need to be improved (DePaola and Toyofuku 2014). As it is known that few fish species use biotoxins for their protection and they are risks to the consumer if consumed inadvertently or intentionally without proper handling. Hence information to consumers in relation to such fishes may be provided by regulatory agencies. Cyanobacteria (blue-green algae) producing cyanotoxins in brackish or freshwater are less known (Moy and Todd 2014) in which some are known most powerful natural poisons. These toxins come through drinking water and occupational and recreational contact. More research in relation to cyanotoxins is the need to hour which will provide base for policymakers to come out with guidelines for protection of human health.

10 Conclusion

Food safety is becoming more and more matter of concern because of globalization and trade. Seafood exports from India have reached a new high in terms of US$ in 2020–2021. The rejection of seafood consignments from different countries was also seen due to various reasons such as filth, bacterial pathogens, biotoxins, etc. Climate change is now felt by each one of us across the world which has major implications in the occurrence of biotoxins. Studies about the emerging biotoxins need to be studied in more comprehensive ways. The analysis of biotoxins takes much time which can be minimized by using rapid methods. Marine biotoxins have been studied in comprehensive way, whereas biotoxins from freshwater are still unknown. Hence there is much need to have understanding on freshwater biotoxins. Regulatory bodies from different countries must carry out regular monitoring of biotoxins in the foods of their region.

References

Ababouch L (2014) Food safety management. In: Motarjemi Y, Moy GG, Todd ECD (eds) Encyclopedia of food safety. Academic Press, Elsevier

Bauer M (ed) (2006) Harmful algal research and response: a human dimensions strategy. National Office for Marine Biotoxins and Harmful Algal Blooms, Woods Hole Oceanographic Institution, Woods Hole, MA, pp I–V

Benson JM, Tischler DL, Baden DG (1999) Uptake, tissue distribution, and excretion of brevetoxin 3 administered to rats by intratracheal instillation. J Toxicol Environ Health A 57(5):345–355

Calicut Research Centre of CMFRI (2011) In: Kaladharan P, Asokan K (eds) India: shellfish poisoning. http://www.prints.cmfri.org.in/9769/1/P_Kaladharan_P_K_Asokan1_Green_Mussel_Farming.pdf/

Cembella AD, Milenkovic L, Doucette G, Fernandez M (1995) Manual on harmful marine microalgae. In: Hallegraeff GM, Anderson DM, Cembella AD (eds) IOC manuals and guides 33. UNESCO, Paris, pp 177–212

Cembella AD, Doucette GJ, Garthwaite I (2003) In vitro assays for phycotoxins. In: Hallegraeff GM, Anderson DM, Cembella AD (eds) Manual on harmful marine microalgae. IOC-UNESCO, Paris, pp 297–345

Chapela MJ, Reboreda A, Vieites JM, Cabado AG (2008) Lipophilic toxins analyzed by liquid chromatography-mass spectrometry and comparison with mouse bioassay in fresh, frozen, and processed molluscs. J Agric Food Chem 56:8979–8986

Christian B, Luckas B (2008) Determination of marine biotoxins relevant for regulations: from the mouse bioassay to coupled LC-MS methods. Anal Bioanal Chem 391(1):117–134

Climent A, Seguel M, Arzul G, Guzmán L, Alarcón C (2001) Widespread outbreak of a haemolytic, ichthyotoxic Gymnodinium sp. in Chile. In: Hallegraeff et al (ed), Harmful algal bloom

Currie BJ (2000) Clinical toxicology: a tropical Australian perspective. Ther Drug Monit 22(1): 73–78

De Fouw JC, Van Egmond HP, Speijers GJA (1999) Ciguatera fish poisoning: a review. RIVM Report No. 388802021

Della LR, Sosa S, Tubaro A (1999) Methodological improvement of the protein phosphatase inhibition assay for the detection of okadaic acid in mussels. Nat Toxins 7:387–392

DePaola A, Toyofuku H (2014) Materials, technologies and risks. In: Encyclopedia of food safety, foods

Draisci R, Lucentini L, Giannetti L, Boria P, Poletti R (1996) First report of pectenotoxin-2 (PTX-2) in algae (Dinophysis fortii) related to seafood poisoning in Europe. Toxicon 34(8):923–935

ECDC (2022). https://www.ecdc.europa.eu/en/marine-biotoxins-2022

EFSA Panel on Contaminants in the Food Chain (CONTAM) (2009a) Scientific Opinion on marine biotoxins in shellfish—palytoxin group. EFSA J 7(12):1393.

EFSA (2009b) EFSA: Scientific opinion of the panel on contaminants in the food chain on a request from the European Commission on marine biotoxins in shellfish—summary on regulated marine biotoxins. EFSA J Agric Food Chem 1306:1–23

EFSA Panel on Contaminants in the Food Chain (2010) Scientific opinion on marine biotoxins in shellfish–emerging toxins: ciguatoxin group. EFSA J 8(6):1627

FAO (2020)

Hallegraeff GM, Anderson DM, Cembella AD (2003) Manual on harmful marine microalgae. Monographs on Oceanographic Methodology, UNESCO, Paris, 11,793 S. (Monographs on oceanographic methodology; 11)

Haywood A (1998) Toxic Gymnodinium update. In: Proceedings of the marine biotoxin science workshop No. 10 (20 November 1998). Marine Biotoxin Technical Committee

Hinder SL, Hays GC, Brooks CJ, Davies AP, Edwards M, Walne AW, Gravenor MB (2011) Toxic marine microalgae and shellfish poisoning in the British isles: history, review of epidemiology, and future implications. Environ Health 10(1):1–12

Jain R, Camarillo MK, Stringfellow WT (2014) Drinking water security for engineers, planners, and managers. Water Distrib Syst:1–12

Khan AS, Swerdlow DL, Juranek DD (2001) Precautions against biological and chemical terrorism directed at food and water supplies. Public Health Rep 116:3–14

Kim CS, Lee SG, Lee CK, Kim HK, Jung J (1999) Reactive oxygen species as causative agents in the icthyotoxicity of the red tide dinoflagellate Cochlodinium polykrikoides. J Plankton Res 21: 2105–2115

Klöpper S, Scharek R, Gerdts G (2003) Diarrhetic shellfish toxicity in relation to the abundance of Dinophysis spp. Ehrenberg 1839 in the German bight near Helgoland. Mar Ecol Prog Ser 259: 93–102

Kreuzer MP, Pravda M, O'Sullivan CK, Guilbault GG (2002) Novel electrochemical immunosensors for seafood toxin analysis. Toxicon 40:1267–1274

Laycock MV, Jellett JF, Belland ER, Bishop PC, Theriault BL, RussellTattrie AL, Quilliam MA, Cembella AD, Richards RC (2001) Mist alert: a rapid assay for paralytic shellfish poisoning toxins. In: Hallegraeff GM, Blackburn SI, Bolch CJ, Lewis RJ (eds) Harmful algal blooms 2000. IOC-UNESCO, Paris, pp 254–256

Leal JF, Cristiano ML (2022) Marine paralytic shellfish toxins: chemical properties, mode of action, newer analogues, and structure–toxicity relationship. Nat Prod Rep 39:33–57

Lehane L (2000) Ciguatera update. Med J Aust 172(4):176–179

Lehane L, Lewis RJ (2000) Ciguatera: recent advances but the risk remains. Int J Food Microbiol 61(2–3):91–125

Leikin J, Paloucek F (1998) Ciguatera food poisoning. In: Poisoning and toxicology compendium. Lexi-Comp Inc., Cleveland, p 783

Mackenzie L, Syhre M, Todd K, Haywood A, Truman P, Garthwaite I, Towers N (1995) DSP and NSP in New Zealand, some recent findings. In: Proceedings of the marine biotoxin science workshop no. 4. Marine Biotoxin Technical Committee

Magdalena AB, Lehane M, Krys S, Fernandez ML, Furey A, James KJ (2003) The first identification of azaspiracids in shellfish from France and Spain. Toxicon 42:105–108

Manger RL, Leja LS, Lee SY, Hungerford JM, Hokama Y, Dickey RW, Granade HR, Lewis R, Yasumoto T, Wekell MM (1995) Detection of sodium channel toxins: Directed cytotoxicity assays of purified ciguatoxins, brevetoxins, saxitoxins, and seafood extracts. J Assoc Anal Chem Int 78:521–527

Micheli L, Radoi A, Guarrina R, Massaud R (2004) Disposable immunosensor for the determination of domoic acid in shellfish. Biosens Bioelectron 20:190–196

Moore SK, Mantua NJ, Hickey BM, Trainer VL (2009) Recent trends in paralytic shellfish toxins in Puget Sound, relationships to climate, and capacity for prediction of toxic events. Harmful Algae 8(3):463–477

Morris S, Algoet M, Turner A (2007a) Advancing shellfish toxin monitoring. Shellfish News 24: 17–20; Oceanography 31(4):132–144. https://doi.org/10.5670/oceanog.2018.403

Morris S, Algoet M, Turner A (2007b) Advancing shellfish toxin monitoring. Shellfish News 24: 17–20

Moy GG, Todd ECD (2014) History, science and methods. In: Encyclopedia of food safety

Ofuji K, Satake M, Oshima Y, McMahon T, James KJ, Yasumoto T (1999) A sensitive and specific determination method for azaspiracids by liquid chromatography mass spectrometry. Nat Toxins 7:247–250

Paterson RRM (2006) Fungi and fungal toxins as weapons. Mycol Res 110(9):1003–1010

Quilliam MA (1996) Liquid chromatography-mass spectrometry of seafood toxins. In: Barcelo D (ed) Applications of LC-MS in environmental science. Elsevier, Amsterdam, pp 415–444

Rafuse C, Cembella AD, Laycock M, Jellett J (2004) Rapid monitoring of toxic phytoplankton and zooplankton with a lateral-flow immunochromatographic assay for ASP and PSP toxins, harmful algae 2002. In: Steidinger KA, Landsberg JH, Tomas CR, Vargo GA (eds) Proceedings of the Xth international conference on harmful algae

Ravn H (1995) HAB Publication Series Volume 1. Amnesic Shellfish

Satake M, Ofuji K, James KJ, Furey A, Yasumoto T (1998) New toxic event caused by Irish mussels. In: Reguera B, Blanco J, Fernandez ML, Wyatt T, (eds) Harmful algae. Xunta de Galicia and Intergovernmental Oceanographic Commission of UNESCO, Santiago de Compostela, pp 468–469

Schantz EJ, Mold JD, Howard WL, Bowden JP, Stanger DW, Lynch JM, Wintersteiner OP, Dutcher JD, Walters DR, Riegel B (1961) Can J Chem 39:2117–2123

Schnorf H, Taurarii M, Cundy T (2002) Ciguatera fish poisoning: a doubleblind randomized trial of mannitol therapy. Neurology 58(6):873–880

Shimizu Y (2000) In: Botana LM (ed) Seafood and freshwater toxins: pharmacology, physiology, and detection. Marcel Dekker, Inc., New York, pp 151–172

Stevens RC, Soelberg DD, Eberhart BT, Sylvester Spencer L, Wekell JC, Chinowsky TM (2007) Detection of the toxin domoic acid from clam extracts using a portable surface plasmon resonance biosensor. Harmful Algae 6:166–174

Suresh SP, Gauri S, Desai S, Kavitha M, Padmavathy P (2014) Marine biotoxins and its detection. Afr J Environ Sci Technol 8(6):350–365

Tillmann U, Borel CM, Barrera F, Lara R, Krock B, Almandoz GO, Witt M, Trefault N (2016) Azadinium poporum from the Argentine Continental Shelf, Southwestern Atlantic, produces azaspiracid-2 and azaspiracid-2 phosphate. Harmful Algae 51:40–55

Turner AD, Goya AB (2015) Occurrence and profiles of lipophilic toxins in shellfish harvested from Argentina. Toxicon 102:32–42

Turrell E, Mckie J, Higgins C, Shammon T, Holland K (2007) Algal toxins in shellfish from Scottish, Northern Irish and Isle of man waters. In: Davidson K, Bresnan E (eds) Relating harmful phytoplankton to shellfish poisoning and human health. Scottish Association for Marine Science, Dunstaffnage Marine Laboratory, Oban, Scotland

Twiner MJ, Rehmann N, Hess P, Doucette GJ (2008) Azaspiracid shellfish poisoning: A review on the chemistry, ecology, and toxicology with an emphasis on human health impacts. Mar Drugs 6(2):39–72

Van Dolah FM, Ramsdell JS (2001) Review and assessment of in vitro detection methods for algal toxins. J Assoc Anal Chem Int 84:1617–1625

Van Dolah FM, Finley BL, Doucette GJ, Moeller PD, Ramsdell JS (1994) Development of rapid and sensitive high throughput pharmacologic assays for marine phycotoxins. Nat Toxins 2:189–196

Varela Martínez C, León Gómez I, Martínez Sánchez EV, Carmona Alférez R, Nuñez Gallo D, Friedemann M, Oleastro M, Boziaris IS (2021) Incidence and epidemiological characteristics of ciguatera cases in Europe, vol 18(5). EFSA Supporting Publications, p 6650E

Vargo GA (2009) A brief summary of the physiology and ecology of Karenia brevis Davis (G. Hansen and Moestrup comb. nov.) red tides on the West Florida shelf and of hypotheses posed for their initiation, growth, maintenance, and termination. Harmful Algae 8(4):573–584

Velayudhan A, Nayak J, Murhekar MV, Dikid T, Sodha SV (2021) Shellfish poisoning outbreaks in Cuddalore District, Tamil Nadu, India. Indian J Public Health 65(5):29

Villalobos LG, Santinelli N, Sastre V, Krock B, Esteves JL (2015) Dinophysis species associated with diarrhetic shellfish poisoning episodes in North Patagonian Gulfs (Chubut, Argentina). J Shellfish Res 34(3):1141–1149

Visciano P, Schirone M, Berti M, Milandri A, Tofalo R, Suzzi G (2016) Marine biotoxins: occurrence, toxicity, regulatory limits and reference methods. Front Microbiol 7:1051

Wright JLC, Quilliam MA (1995) Methods for domoic acid, the amnesic shellfish poisons. In: Hallegraeff GM et al (eds) Manual on harmful marine microalgae. IOC Manuals and Guides No. 33. UNESCO, pp 113–133

Wright JLC, Boyd RK, De Freitas ASW, Falk M, Foxall RA, Jamieson WD, Laycock MV, McCulloch AW, McInnes AG, Odense P, Pathak VP, Quilliam MA, Ragan MA, Sim PG, Thibault P, Walter JA, Gilgan M, Richard DJ, Dewar D (1989) Identification of domoic acid, a neuroexcitatory amino acid, in toxic mussels from eastern Prince Edward Island. Can J Chem 67:481–490

Yasumoto T, Oshima Y, Yamaguchi M (1978) Occurrence of a new type of shellfish poisoning in the Tohoku district. Bull Japan Soc Sci Fish 44:1249–1255

Zingone A, Escalera L, Aligizaki K, Fernández-Tejedor M, Ismael A, Montresor M, Mozetič P, Taş S, Totti C (2021) Toxic marine microalgae and noxious blooms in the Mediterranean Sea: a contribution to the global HAB status report. Harmful Algae 102:101843

Part III

Prioritization of Fish Feed Technology with Respect to Changing Climate for Adaptation and Mitigation

Metabolomic Response to High Temperature Stress in Murrel *Channa striatus* and Insights for Designer Feeds

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Abstract

Aquaculture is among the most important food production sectors and plays an extremely important role in ensuring food and nutritional security across the globe. However, climate change and resulting global warming is posing challenges for the aquaculture sector. Fish growth, reproductive capability, resistance to diseases and health in general would be severely affected by high temperature. In order to ensure sustainable growth of the sector, it is necessary to look for ameliorative strategies. The feed based approach is among the most viable ameliorative strategies. However, the development of medicated feeds has been mostly done through heat and trial method making it a time consuming process. Inversely, the development of metabolomics has opened door for a new

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approach in which metabolic responses of an organism under a particular stress could be studied and depending upon the physiological requirement, specific ingredients could be incorporated in the diet for preparation of designer feeds. The present chapter describes how the metabolomic responses of murrel *Channa striatus* could be utilized for preparation of designer feeds for ameliorating heat stress. Although heat stress has been used as a case study, the scope of the approach could be extended to other stressors also.

Keywords

Aquaculture · Metabolomics · Designer feed · Fish nutrition · Heat stress

1 Introduction

Temperature has a significant impact on biological organisms' physiology. As a result, a change in the ambient temperature from its ideal value can affect several homeostatic functions. High temperature has a severe influence on poikilothermic animals like fish, affecting growth, reproduction, and even death: all of these factors are likely to contribute to a loss of overall output in a pisciculture situation (Acton 2012; Allan et al. 2015; Mahanty et al. 2019). According to the assessment report submitted by the Intergovernmental Panel on Climate Change, 20% of the known species of fish will face the risk of extinction if the mean global temperature rises by 1.5–2 °C (IPCC 2007, 2022; Mahanty et al. 2016, 2017; Mohanty et al. 2010, 2017). The mean atmospheric temperature has risen by 0.8 °C in the last 133 years and unless steps are taken the increment may exceed 1.2 °C. High temperature (heat) waves, a prolonged period of excessive hot weather have also caused a lot of human and animal deaths in recent times.

Akin to the effect of heat stress on humans and other animals, heat stress has also affected fish and shellfish physiology, health, reproduction, and consequently the aquaculture and fisheries production. Aquaculture and fisheries are among the fastest growing food production sectors in the world. Fish is an important component of human diet and provides all necessary nutrients absent in typical starchy staple foods (FAO 2005). Fish provides about 1/5th of total animal protein intake and is one of the most affordable sources of animal proteins (Thorpe et al. 2006). Other than protein, fish is also a good source of polyunsaturated fatty acids and micronutrients (vitamins and minerals) (FAO 2005; Mahanty et al. 2014). Global rise in temperature is affecting the distribution and composition of species and overall production in marine and freshwater aquaculture systems (Brander 2007; Misganaw et al. 2015). It has been predicted that climate change can have a variable impact on the fisheries and aquaculture production depending on species, geographical area and distribution. For instance, the elevated winter temperature would result in increased production of salmonids but at the same time it could also increase the chances of infections. Moreover, the increased summer temperature would result in high mortality of fishes (Moth-Poulsen 2016).

To cope with any stress, whether biotic or abiotic, physiological and metabolic readjustments in the pathways of carbohydrate, lipid and protein metabolism are expected. These may have their characteristic markers or fingerprints in the metabolome that need to be identified for understanding the mechanism of thermotolerance. Therefore, changes in amino acid and fatty acid profiles of muscle/liver tissues of heat-stressed *Channa striatus* have been studied. The findings of the study would be useful in understanding the metabolomics readjustments occurring under high temperature and could be usefully harnessed to develop feed based strategies to mitigate temperature stress in aquacultured animals.

2 Atri Hot Spring: Nature's Own Laboratory for Global Warming Research

Adaptation to changing environment is necessary for survival of a species. The adaptation pressure created by environment has led to the development of anti-freeze protein in Antarctic fishes. Akin to these fishes, organisms constantly facing high temperatures stress like those inhabiting runoffs of hot springs are expected to have adapted to the harsh condition and can provide clues on the mechanism of high temperature stress tolerance.

Atri hot spring situated in the state of Odisha, India has been found to be an ideal place for studying the mechanism of heat stress tolerance. The major source of the spring in Atri is a circular tank with a temperature of 57–58 °C. To avoid stagnation, the water from this tank is channeled through cemented tank exits, where it is used for bathing. The exit, which conveys the 38 °C hot-spring runoff water, joins to a neighboring rivulet, a tributary of the river Rana nadi; the temperature of the confluence and immediate periphery remains around 36–38 °C. In the confluence zone, which is exposed to the high temperature, fish such as *Channa striatus*, *Puntius sophore*, and other minor carps have been found. The fishes that live in this area have adapted to the heat, making them excellent models for researching the effects of high temperature (Mohanty et al. 2014).

3 Amino Acids as Important Metabolites

Amino acids are essential chemicals that function as both protein building blocks and metabolic pathway intermediates (Vonwachlendonk and Kappler 1977). They are used to make a variety of biologically significant chemicals, such as nucleotides, peptide hormones, and neurotransmitters. Furthermore, amino acids are significant regulators of gene expression and protein phosphorylation cascades in animal cells (Wu 2013), food transport and metabolism in animal cells (Wang et al. 2013), and innate and cell-mediated immunological responses (Wang et al. 2013).

Amino acids are primarily derived through proteins in the diet, and the essential to non-essential amino acid ratio is used to determine the quality of dietary protein. High-quality proteins are easily digested and contain sufficient amounts of dietary essential amino acids (EAA) to meet human needs. Proteins, the most abundant macromolecules in biological systems, come in a variety of forms, including structural components, enzymes, hormones, antibodies, receptors, signaling molecules, and other biologically important molecules. Protein is required for a variety of bodily processes, including the provision of vital amino acids as well as tissue formation and maintenance. Essential, non-essential, and conditionally essential amino acids are the three types of amino acids. Essential amino acids are those that are neither produced or insufficiently generated in the body and must thus be obtained from food. Animals can adequately manufacture non-essential amino acids; however, conditionally necessary amino acids must be obtained from the diet under conditions where use exceeds production (Wu 2013). The essential amino acids include arginine, histidine, isoleucine, leucine, lysine, valine, threonine, methionine, and phenylalanine, while non-essential amino acids include proline, tyrosine, glutamic acid, glycine, alanine, aspartic acid, serine, and cysteine (Wu 2013).

4 Changes in Amino Acid Metabolome of *Channa striatus* Under High Temperature Stress

The present study was carried out to examine the altered amino acid profile in the liver and muscle tissues of *Channa striatus* collected from the hot spring runoff. Figure 1 shows the changes in essential and non-essential amino acids in the liver and muscle tissues of *Channa striatus.*

The study showed significant changes in the level of EAA histidine and glycine and significant decrease in arginine, isoleucine, and lysine in the fishes inhabiting the hot spring runoff (Tables 1 and 2).

Depending on the developmental stage, function, and health status of an individual, arginine is classed as an essential or conditionally essential amino acid (Tapiero et al. 2002). In terrestrial mammals, it is one of the most versatile AAs, serving as a precursor for the production of protein, nitric oxide (NO), urea, polyamines, proline, glutamate, creatine, and agmatine (Wu and Morris 1998). Arginine also aids in the prevention of heat-related fatalities (Costa et al. 2014). Arginine, as a precursor of nitric oxide, plays a function in the treatment of several illnesses that necessitate vasodilation (Tapiero et al. 2002). The expression of hsp70 protein in the liver was significantly reduced when L-arginine was added to the diet of heat-stressed mice (Chatterjee et al. 2005). In the present study, the AA level of arginine in liver tissue decreased (1.18-fold) during hot spring thermal exposure as compared to control.

Histidine is a precursor of histamine and plays many roles in protein interaction (Liao et al. 2013). It is also necessary for tissue growth and repair, the preservation of myelin sheaths, and the removal of heavy metals from the body (Heimann 1982). Surprisingly, intramuscular histidine concentrations rise dramatically prior to salmon spawning migration (Mommsen et al. 1980). Histidine metabolism and nutritional requirements in fish may be influenced by a variety of environmental and endocrine factors. Plasma has a high concentration of a histidine-rich glycoprotein with a multidomain structure that regulates a variety of biological processes such

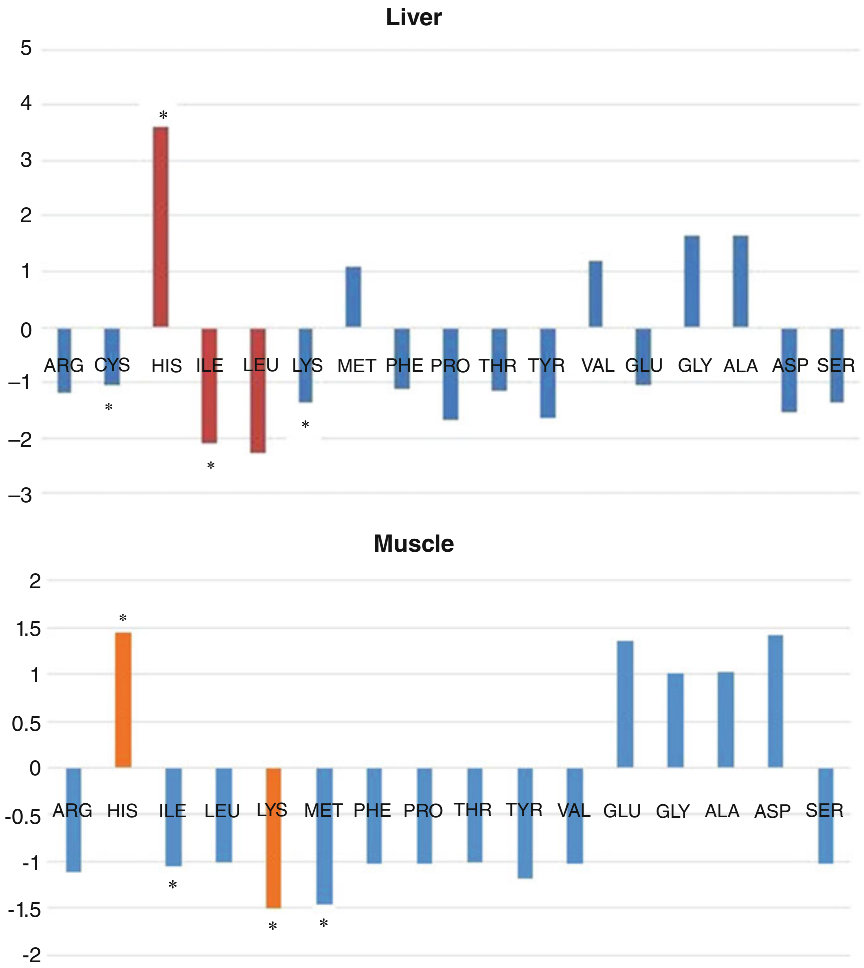

Fig. 1 Changes in liver and muscle amino acid profile of *Channa striatus* collected from the hot spring runoff. * denotes significant change ($p > 0.05$). Bars in orange denote considerable change in the amino acid content in the hot spring runoff fish

as cell adhesion and migration, complement activation, immune complex clearance, and phagocytosis of apoptotic cells. Histidine decarboxylase, for example, initiates an immunologically significant pathway for histidine utilization by producing histamine, a prominent mediator of inflammatory reactions (Tanaka and Ichikawa 2006). To synthesize histamine, several organs and cell types express the histidine decarboxylase enzyme. By activating multiple histamine receptors on target cells, histamine modulates a variety of physiological and immunological processes. In addition to histamine synthesis, histidine can be deaminated to create urocanic acid by the catalytic enzyme histidine-ammonia lyase (UCA). This chemical is a one-of-a-kind

Table 1 Comparative amino acid profile of liver of *Channa striatus* collected from Atri hot spring runoff

Liver			
Amino acid	Control (% area)	Hot spring (% area)	*p*-value
ARG	13.38	11.32	0.0312
CYS	1.33	1.22	0.009
HIS	5.63	22.54	0.001
ILE	18.21	8.58	0.0011
LEU	10.84	4.8	0.1576
LYS	5.72	3.46	0.001
MET	4.1	4.5	0.1973
PHE	6.27	6.1	0.1575
PRO	1.3	0.78	0.079
THR	2.96	2.58	0.1867
TYR	2.73	1.66	0.20
VAL	3.53	4.16	0.1265
GLU	4.63	4.5	0.35
GLY	11.28	18.55	0.0127
ALA	2.81	2.81	0.484
ASP	2.16	1.4	0.057
SER	2.96	2.17	0.11

Fishes collected from aquaculture ponds served as control

Table 2 Comparative amino acid profile of muscle *Channa striatus* collected from Atri hot spring runoff

Liver			
Amino acid	Control (% area)	Hot spring (% area)	*p*-value
ARG	5.44	4.92	0.09
HIS	5.81	8.37	0.01
ILE	10.41	9.88	0.01
LEU	18.5	18.41	0.42
LYS	4.46	2.89	0.03
MET	3.46	2.33	0.04
PHE	9.68	9.47	0.15
PRO	1.65	1.61	0.15
THR	4.48	4.45	0.06
TYR	2.17	1.84	0.10
VAL	8.49	8.29	0.06
GLU	3.03	4.1	0.04
GLY	5.86	5.81	0.12
ALA	7.86	8	0.22
ASP	2.44	3.44	0.06
SER	5.86	5.78	0.11

Fishes collected from aquaculture ponds served as control photoreceptor, and its conversion from cis-UCA to trans-UCS regulates the onset of solar ultraviolet-immune B's suppressive activity (De Fabo and Noonan 1983).

Isoleucine is a branched chain amino acid that is essential for muscle development and growth (Charlton 2006). Patients on hemodialysis for chronic renal failure (CRF) had low plasma levels of the branched chain amino acids (BCAA) leucine, isoleucine, and valine. Appropriate high protein supplements can be used to rectify anomalies in the plasma amino acid pool (Vuzelov et al. 1999).

Etzel (2004) identified leucine as the sole dietary amino acid capable of stimulating muscle protein synthesis, and it has an essential therapeutic function in stress conditions such as burns, trauma, and other types of stress (De-Bandt and Cynober 2006). Leucine is a dietary supplement that has been shown to reduce muscle tissue deterioration by enhancing muscle protein synthesis.

Glycine is involved in metabolic control, tissue injury prevention, anti-oxidant activity enhancement, protein synthesis and wound healing, as well as boosting immunity, metabolic disorders therapy, and numerous inflammatory illnesses treatment (Wang et al. 2013). Because of its lower side chain activity, glycine is a non-chiral proteogenic amino acid that can easily fit in both hydrophobic and hydrophilic environments. Glycine betaine, a methyl amine of glycine, acts as a chemical chaperone (Tomanek 2010), and the enzymes involved in glycine betaine synthesis have been discovered to be changed during heat stress (Podrabsky and Somero 2004). It was previously observed that thermally stressed bleaching corals had increased expression of glycine-rich RNA binding protein (Bellantuono et al. 2012). As a result, higher synthesis of glycine-rich proteins and glycine-derived chemical chaperones can be attributed to increased glycine concentration in the thermotolerant fish liver. Glycine levels were upregulated (1.25 fold, 1.64 fold in muscle and liver respectively) in hot spring runoff fishes as compared to the control.

5 Epilogue

Significant alterations in histidine, isoleucine, leucine, glycine and lysine content was observed in the host spring runoff fishes indicating a clear metabolic readjustment in the amino acid metabolome which is perhaps governed by the natural selection pressure to ensure survival of the organism in the hostile environment. Earlier our studies on fatty acid composition of *Channa striatus* inhibiting hot spring runoff indicated higher levels of MUFA and PUFA fatty acids at higher acclimation temperature. In liver, 18:1 trans fatty acid content was higher when the fish was exposed to 36 °C and beyond. Also, in both liver and muscle of *Channa striatus* collected from the hot spring runoff, increase in temperature significantly increased the total saturated fatty acids (SFAs), palmitic acid, and stearic acid (Purohit et al. 2018). Taking cues from the study, these amino acids could be incorporated in the diets of aquaculture fishes to mitigate the impacts of thermal stress.

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References

Acton QA (2012) Advances in research and application. Scholarly edition, Atlanta, GA

Allan BJM, Domenici P, Munday PL, McCormick MI (2015) Feeling the heat: the effect of acute temperature changes on predator–prey interactions in coral reef fish. Conserv Physiol 3(1): cov011

Bellantuono AJ, Granados-Cifuentes C, Miller DJ, Hoegh-Guldberg O, Rodriguez-Lanetty M (2012) Coral thermal tolerance: tuning gene expression to resist thermal stress. PLoS One 8 (10):10

Brander KM (2007) Global fish production and climate change. Proc Natl Acad Sci USA 104(50): 19709–19714

Charlton M (2006) Branched-chain amino acid enriched supplements as therapy for liver disease. J Nutr 136(1):295S–298S

Chatterjee S, Premachandran S, Sharma D, Bagewadikar RS, Poduval TB (2005) Therapeutic treatment with L-arginine rescues mice from heat stroke-induced death: physiological and molecular mechanisms. Shock 24(4):341–347

Costa KA et al (2014) L-arginine supplementation prevents increases in intestinal permeability and bacterial translocation in male Swiss mice subjected to physical exercise under environmental heat stress. J Nutr 144(2):218–223. https://doi.org/10.3945/jn.113.183186

De Fabo EC, Noonan FP (1983) Mechanism of immune suppression by ultraviolet irradiation in vivo. I. Evidence for the existence of a unique photoreceptor in skin and its role in photoimmunology. J Exp Med 158(1):84–98

De-Bandt J, Cynober L (2006) Therapeutic use of branched chain amino acids in burn, trauma, and sepsis. J Nutr 185(1):308S–313S

Etzel M (2004) Manufacture and use of dairy protein fractions. J Nutr 134(4):996S–1002S

FAO (2005) Increasing the contribution of small-scale fisheries to poverty alleviation and food security, vol 10, p 79. FAO Technical Guidelines for Responsible Fisheries

Heimann W (1982) Fundamental of food chemistry. AVI Publishing Company, Westport, CT

IPCC (2007) Fourth assessment report—climate change 2007: synthesis report. IPCC, Geneva

IPCC (2022) Sixth assessment report—climate change 2022: synthesis report. IPCC, Geneva

Liao S, Du Q, Meng J, Pang Z, Huang R (2013) The multiple roles of histidine in protein interactions. Chem Central J 7:44

Mahanty A, Ganguly S, Verma A, Sahoo S, Paria P, Mitra P, Singh BK, Sharma AP, Mohanty BP (2014) Nutrient profile of small indigenous fish *Puntius sophore*: proximate composition, amino acid, fatty acid and micronutrient profiles. Natl Acad Sci Letts 37(1):39–44

Mahanty A, Purohit GK, Banerjee S, Karunakaran D, Mohanty S, Mohanty BP (2016) Proteomic changes in liver of *Channa striatus* in response to high temperature stress. Electrophoresis 37(12):1704–1717

Mahanty A, Purohit GK, Yadav RP, Mohanty S, Mohanty BP (2017) hsp90 and hsp47appear to play an important role in minnow *Puntius sophore* for surviving in the hot spring runoff aquatic ecosystem. Fish Physiol Biochem 43(1):89–102

Mahanty A, Purohit G, Mohanty S, Mahanty BP (2019) Heat stress–induced alterations in the expression of genes associated with gonadal integrity of the teleost Puntius sophore. Fish Physiol Biochem 45:1409–1417

Misganaw K, Bazezew M, Getu A (2015) Review work on the impact of climate change on fish and fisheries. Global Res J Fish Sci Aquacult 2(1):015–019

Mohanty BP, Mohanty S, Sahoo J, Sharma AP (2010) Climate change: impacts on fisheries and aquaculture. In: Simard S (ed) Climate change and variability. IntechOpenhttps://www.intechopen.com/chapters/11440, London. https://doi.org/10.5772/9805

Mohanty S, Mahanty A, Yadav RP, Purohit GK, Mohanty BN, Mohanty BP (2014) The Atri Hot Spring in Odisha – a natural ecosystem for global warming research. Int J Geol Earth Environ Sci 4(1):85–90

Mohanty BP, Vivekanandan E, Mohanty S, Mahanty A, Trivedi R, Tripathy M, Sahu J (2017) The impact of climate change on marine and inland fisheries and aquaculture in India. In: Phillips BF, Pérez-Ramírez M (eds) Climate change impacts on fisheries and aquaculture: A global analysis, I. https://doi.org/10.1002/9781119154051.ch17

Mommsen T, French C, Hochachka P (1980) Sites and patterns of protein and amino acid utilization during the spawning migration of salmon. Can J Zool 58:1785–1799

Moth-Poulsen T (2016) Effect of climate change on fisheries and aquaculture with emphasis on Central and Eastern Europe

Podrabsky JE, Somero GN (2004) Changes in gene expression associated with acclimation to constant temperatures and fluctuating daily temperatures in an annual killifish Austrofundulus limnaeus. J Exp Biol 207(13):2237–2254

Purohit GK, Mahanty A, Mohanty S, Mohanty BP (2018) Changes in fatty acid composition in murrel channa striatus in response to acute and chronic high temperature stress. RDWU Bull Sci II:140–146

Tanaka S, Ichikawa A (2006) Recent advances in molecular pharmacology of the histamine systems: immune regulatory roles of histamine produced by leukocytes. J Pharmacol Sci 101(1):19–23

Tapiero H, Mathe G, Couvreur P, Tew KD (2002) I. Arginine. Biomed Pharmacother 56(9): 439–445

Thorpe A, Reid C, Anrooy RV, Brugere C, Becker D (2006) Poverty reduction strategy papers and the fisheries sector: an opportunity forgone. Int J For Hortic 4:487–488

Tomanek L (2010) Variation in the heat shock response and its implication for predicting the effect of global climate change on species' biogeographical distribution ranges and metabolic costs. J Exp Biol 213(6):971–979. https://doi.org/10.1242/jeb.038034

Vonwachlendonk D, Kappler M (1977) Amino acids and biogenic amines in smooth muscles and haemolymph of different mollusks. Comp Biol Chem Physiol 56:19–24

Vuzelov E, Krivoshiev S, Ribarova F, Boyadjiev N (1999) Plasma levels of branched chain amino acids in patients on regular hemodialysis before and after including a high-protein supplement in their diet. Folia Med 41(4):19–22

Wang W, Wu Z, Dai Z, Yang Y, Wang J, Wu G (2013) Glycine metabolism in animals and humans: implications for nutrition and health. Amino Acids 45(3):463–477

Wu G (2013) Functional amino acids in nutrition and health. Amino Acids 45(3):407–411. https://doi.org/10.1007/s00726-013-1500-6

Wu G, Morris SM Jr (1998) Arginine metabolism: nitric oxide and beyond. Biochem J 336:1–17

Feed and Feeding Management for Sustainable Growth and Health of Fish in Varying Climatic Conditions

Shivendra Kumar and Aditi Banik

Abstract

Climate change's impact on inland fisheries has risen to the top of the priority list in the past few years, owing to its direct and potential effects on the environment and human society, particularly food security. It has the potential to have a considerable impact on inland fisheries in terms of water resources, biological diversity, productivity, and sustainability. Aside from profitability, aquaculture operations are expected to be impacted in terms of productivity and agricultural procedures. Although this occurrence cannot be avoided, certain mitigation strategies and management techniques can help to reduce adverse implications and increase resilience in the face of adversity. Various processes are excavated to get rid of it. It involves using exogenous enzymes including the effects of programming documented in fishes based significantly on survival, growth, brain development, and nutrient metabolism. Additionally, another technique like mixed feeding schedules can be brought into play as a strategy in aquaculture to support fish development and well-being in the face of changing climatic conditions.

Keywords

Climate change · Aquaculture · Sustainability · Exogenous enzymes · Mixed feeding schedules · Mitigation strategies · Nutritional programming

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1 Introduction

Aquaculture is a method of achieving long-term sustainability in the production of aquatic items. Harvest stagnation in wild fisheries and overexploitation were the reasons that made to grow the demand for the domestication of economically important species. As aquaculture continues to grow commercially, the demand for cost-effective aquatic feeds gets elevated to bag an inflated marginal profit. Aquaculture's contribution to world fish output has continued to climb, reaching 82.1 million tonnes (46%) of the predicted 179 million tonnes of global production, according to FAO (2020). Furthermore, aquaculture is expected to grow its share of global fish production from 46 percent currently to 53% in 2030 (Food and Agriculture Organization of the United Nations 2020).

Aquatic animals have a wide range of nutritional requirements and are grown in a variety of ways (e.g. in ponds, rivers, open water net-pens, or land-based tanks) (Fry et al. 2016). According to UNFAO (2014), feed is required for approximately two-thirds of the production of farmed aquatic animals. The most pressing question, however, is whether the sector can grow sustainably and quickly enough to satisfy future predicted demand, which is being worsened by a rapidly growing human population and a changing environment. Climate change is currently seen as a major threat to the world food supply, both in terms of quality and quantity (Myers et al. 2017). The expected effects of climate change are putting food security, particularly access to dietary protein, in jeopardy (Kandu 2017).

Climate change is currently a major source of concern for human society. It has been labeled a big worldwide issue for contributing to rising ocean temperatures and acidification. Both in the ocean and freshwater, it has an impact on fish distribution and productivity. Many people support fisheries and aquaculture intending to improve their social position, even though fish is a high-protein, flavorful food.

The main ground for climate change is global warming. In its fourth assessment report, the Intergovernmental Panel on Climate Change (IPCC) came to the fact that this condition gave a big pay-off due to uncontrollable emission of harmful greenhouse gas from the combustion of fossil fuel to generate energy including transport and industry followed by deforestation, intensive agriculture, other anthropogenic activities. Abiotic variables substantially altered the environment, both directly and indirectly, to harm an organism's population performance or individual physiology (abiotic stress) (FAO 2020).

2 The Implications of Climate Change on Aquaculture and Fisheries

Plants and poikilothermic animals are dealt with in fisheries and aquaculture because they are more subject to temperature fluctuations in the ambient environment induced by climate change (Table 1). Though point consequences are yet to be known, fisheries and aquaculture, as well as their dependent communities and related economic activities, are anticipated to be impacted by climate change in three ways:

Table 1 Impact of climate change on the biology of farmed fishes

The extent of the impact on fishes	Effects on fisheries	References
Physiological function	Temperature and dissolved oxygen have an impact on fish performance as well as an individual's ability to flourish and develop to a fishable size	Pörtner and Peck (2010), Harrod (2015)
Growth rate affecting body size	This has a direct impact on fish yield because it is linked to physiological function. The temperature has a big impact on this	Ohlberger (2013), Harrod (2015)
Metabolic rate inducing growth and reproductive capacity	Fish must expend more energy to sustain their metabolic condition as water temperatures dip beyond individual thresholds, lowering the amount of energy available for somatic growth (potential yield) or gonadal investment (capacity of fish to replace themselves)	Holkeret et al. (2003), Harrod (2015)
Duration of the life span of fishes	The amount of time it takes for fish to complete their life cycle and recruit to the fishery. If hatching does not coincide with abundant food or suitable conditions, there is a risk of larval mortality (and a shortage of supply for the fishery). Variations in river flow timing, temperature, rainfall cues, and seasonal fertility in water bodies are all linked to climate change	Lappalainen et al. (2008), Harrod (2015)
Reproduction and reproductory behavior	Many fish's reproductive cycles and breeding behavior are influenced by seasonal changes in temperature or water levels. Alteration in these elements may have an impact on fisheries' propagation and population dynamics	Pankhurst and Munday (2011), Harrod (2015)
Response to immunity leading to disease outbreak	Variations in temperature, flow, depth, and other factors can alter a fish's ability to resist infection as well as the likelihood of contracting disease and parasites, affecting growth and potential productivity	Harrod (2015)

(continued)

Table 1 (continued)

The extent of the impact on fishes	Effects on fisheries	References
Migratory behavior	Environmental cues for migration are typically environmental (water level, flow, temperature), and if conditions alter, this can affect the timing and size of migration in fish, as well as create obstacles to migration, affecting breeding, survival, as well as productivity	Wedekind and Kung (2010), Shuter et al. (2012), Warren et al. (2012), Harrod (2015)
Encounter with stressors	Increased pollutant concentrations and absorption can occur as a result of higher water temperatures and lower flow/water levels, lowering the quality or acceptability of the catch for food Extreme weather occurrences have short-term consequences (e.g. high or low temperature). Individual growth and performance are affected, as well as mortality, impacting the quality and size of the fishable stock	Bullock and Coutts (1985), Coutant (1986), Schindler et al. (1996), Reid (1997), Zagarese and Williamson (2000), Wrona et al. (2006), Reist et al. (2006), Häder et al. (2007), Schiedek et al. (2007), Noyes et al. (2009), Harrod (2015)
Epigenetics	These are phenotypic alterations caused by temperature-influenced gene responses that are relatively short or quick. This has an impact on fishery professionals' ability to predict stock characteristics	Salinas and Munch (2012), Harrod (2015)
Fish community relating to interspecific interactions and biodiversity loss	Affects the strength and form of ecological interactions among species, thereby lowering the capability of prediction of associated ecosystem function	De Stasio et al. (1996), Jeppesen et al. (2010), Blois et al. (2013), Dell'Apa et al. (2013), Hayden et al. (2013), Harrod (2015)

1. Indirect socioeconomic consequences on a larger scale
2. Biological and ecological responses to changes in the environment
3. Immediate physical consequences

Now, let us get a brief idea of the following pathways.

2.1 Indirect Wider Socioeconomic Effects

The state of the environment is changing in many ways, but the most concerning aspect is how natural habitats have been intensively exploited for diverse purposes. These rapid and frequently unanticipated changes have sparked disputes among resource-dependent livelihoods in the inland fishing industry. Land-use change, intensification of resource extraction, urbanization, industrial growth, tourism, and recreational demand all contribute to increased environmental pressure. As a result, conflicts over the use of freshwater have an impact on all food production systems, while other sectors' adaptation and mitigation measures have an impact on aquatic systems in general, as well as fisheries and aquaculture in particular.

2.2 Biological and Ecological Responses to Physical Changes

Productivity, species abundance, ecosystem stability, stock locations, and disease levels are all affected significantly.

2.3 Direct Physical Effects

Flooding, storm impacts, and changes in the water level.

3 Challenges in Nutrition Utilization in Changing Climate

3.1 Inhibitors in Aquaculture Systems

Climate change and its impacts, such as global warming, are now being felt all across the world, along with changes in the climate pattern. Extreme weather events such as flooding, droughts, heavy precipitation, rising water temperatures, and ecological drifts have become more common as a result of this. Fish, as poikilothermic animals, are easily affected by temperature variations. Hydrological stress and variations in water quality can be caused by changes in water temperature (Nowicki et al. 2019). Furthermore, a temperature rise can lower oxygen levels in the aqueous medium, resulting in hypoxic stress. Temperature changes can suffocate the growth of natural food species, particularly planktons, resulting in calorie limitation and hunger. These stresses can generate oxidative stress at the cellular level, which could lead to a fish antioxidant system imbalance. All of these stimuli can cause acute and chronic stress reactions in fish, known as "general adaptive syndrome (GAS)." Diminished feed intake, decreased digestion, metabolism, and absorption, weakened immunological and antioxidant systems, and reduced overall growth of fish are all possible outcomes. Weakened immunity can make disease outbreaks in the system more easily.

3.2 Physiological Changes Owing to Stress

Climate change is endangering a wide range of fish species, habitats, and aquaculture systems by causing extreme temperature (hot and cold) events (Islam et al. 2021). Temperature changes have an impact on all biochemical and physiological functions of fish, including growth, feed intake, reproduction, survival, behavior, and distribution (Debnath et al. 2006; Islam et al. 2021). Pörtner and Peck (2010) found that changing the energetic cost of physiological homeostasis may cause significant mortality in fish during extreme weather conditions (Madeira et al. 2016; Zhou et al. 2018; Pattanaik et al. 2017). Temperature variations are expected to affect fish homeostasis and produce physiological stress in aquatic species, but they also have certain beneficial benefits. Aquaculture has been demonstrated to benefit from temperature increases up to a certain point by enhancing growth rates and food conversion efficiency. For example, Das et al. (2005) discovered that the optimal temperature for *Labeo rohita* development and better feed efficiency was 31–33 °C, which was higher than the previously reported range of 24–26 °C (Kausar and Salim 2006). The excessive temperature outside of a species' ideal temperature range, however, has a detrimental impact on aquatic animal health because the need for oxygen rises owing to metabolic stress, and disease vulnerability climbs as well (Wedemeyer et al. 1999). Furthermore, the development of innate and acquired immunity in fish is influenced by ambient water temperature, with elevated water temperatures causing a decrease in white blood cells, total protein, albumin, and globulin in *Cyprinus carpio* and *Tor putitora* (Verma et al. 2007; Akhtar et al. 2013).

4 Feed and Feeding Strategies to Mitigate Climate Change Stress

4.1 Exogenous Enzymes in Fish Feed

A major concern with the alternative plant ingredients used in fish meal replacement diets is the presence of a wide variety of antinutritional substances such as tannin, gossypol, phytic acid, erucic acid, etc. Though the two most frequent detoxification procedures utilized to tide over most antinutritional elements are heat inactivation and water soaking. Enzymes provide a natural means to convert complicated feed components into nutrients that can be absorbed (Felix and Selvaraj 2004). These are one kind of enzymes added externally being incorporated in the fish feed implemented globally. Despite knowing the chemical effects of the respective exogenous enzymes its use and impact on the fishes consuming the fish feed are still unknown (Zheng et al. 2020).

The most possible reasons for the exogenous enzymes (Table 2) to be used in the fish diet are:

Improvement in digestibility and utilization of feed (Figs. 1 and 2): Scientists have worked a lot to excavate the beneficial activities of the enzymes when implemented into the fish diet (Ali et al. 2007). Additionally, cereals and

Table 2 Summary of exogenous enzyme studies using fish models

Exoenzyme stimuli	Enzymatic features	Species	Effects	References
A low-protein diet supplemented with protease	Supplement the deficiency of endogenous proteases to break down macromolecular protein to a smaller unit of peptides and amino acids that can readily be digested and absorbed	Juvenile gibel carp	Reduction in the dietary protein requirement Reduced FCR The nutrient digestibility has improved considerably The muscle layer thickness got reduced Promotes the growth of fish	Liu et al. (2018)
Exogenous protease added into extruded canola: pea-based diet		Rainbow trout	Increase in feed efficiency Improved utilization of nutrients	Drew et al. (2005)
Exogenous protease supplementation to flax: OEA-based diet		Rainbow trout	No significant effect on nutrient digestibility is observed	Drew et al. (2005)
α-Amylase (50 mg/kg) supplemented gelatinized and non-gelatinized corn diets	Hydrolyze the glycosidic linkages in starch molecules, converting complex carbs to simple sugars	*Labeo rohita* fingerlings	The superior performance of non-gelatinized corn-fed fish ↑Intestinal amylase and protease activity Better growth and utilization of protein ↑Blood glucose and glucose 6 phosphate dehydrogenase activity in the liver Activities of glucose 6 phosphate and fructose-1,6-bisphosphate↓	Kumar et al. (2006, 2009)
Exoenzyme complex of highly purified NSP (endo-1,4-beta-xylanase and endo-1,4-beta-glucanase)	Endohydrolysis of xylosidic bonds in xylan, a critical carbon source for cellular metabolism, which is required for the formation of xylose	Turbot (*Scophthalmus maximus*)	Increased apparent digestibility coefficient of protein and lipid Promotion in the activity of the digestive enzyme in the posterior intestine	Diógenes et al. (2018)

(continued)

Table 2 (continued)

Exoenzyme stimuli	Enzymatic features	Species	Effects	References
Xylanase supplemented to rapeseed meal (260 g/kg) based diet		Rainbow trout	Positively affecting apparent lipid digestibility	Dalsgaard et al. (2012)
Exogenous xylanase and phytase in DORB-based diet		Rohu	Improvement in physiological status and growth performance	Ranjan et al. (2021)
Supplementation of exogenous enzyme cocktail (pentosanase + cellulase + xylanase)		*Lateolabrax japonicus*	Effectively reduces the antinutritional factors An increase in phosphorus retention and protein utilization leads to better growth performance	Ai et al. (2007)
Supplementing β glucanase into a diet containing 344 g/kg soybean meal		Rainbow trout	Improvement in apparent digestibility of all dietary nutrients	Dalsgaard et al. (2012)
B glucanase added to 250 g/kg sunflower meal-based diet		Rainbow trout	Improved apparent digestibility of lipids	Dalsgaard et al. (2012)
Cellulase supplemented diet	Catalyzes cellulose polysaccharide breakdown	*Carassius auratus*	Improved growth performance, digestive activity, and nutrient digestibility	Shi et al. (2017), Cao et al. (2017), Huang and Huang (2004)
Cellulase (3 g/kg) supplemented duckweed-based diet		Grass carp	Increased intestinal digestive enzyme activities	Zhou et al. (2013)
Multienzyme complex (phytase + xylanase + β glucanase + β amylase + cellulose + pectinase) supplanted		African catfish Great sturgeon Caspian salmon	Positive growth performance and feed efficiency	Yildirim and Turan (2010), Ghomi et al. (2012) and Zamini et al. (2014)
500 mg/kg multienzyme complex supplemented		Sturgeon fingerlins (Husohuso)	Elevation in the content of higher n3 essential fatty acids n-3/n-6 fatty acid ratio lowered	Ghomi et al. (2012)

Cellulase enzyme (1–5 g/kg) product on canola meal-based diet	Catalyzes cellulose polysaccharide breakdown	*Oreochromis niloticus*	No impact on growth performance, body composition, and nutrient digestibility	Yigit and Olmez (2011)
Exogenous lipase supplementation	Free fatty aids and glycerol are formed when triglycerides are broken down	Young grass carp	Increased acid phosphatase activity Upregulation in the relative mRNA levels of antimicrobial peptides, anti-inflammatory cytokines as well as signaling molecule inhibitor protein	Liu et al. (2016)
Dietary lipase supplementation		Rainbow trout	No influence on growth, fillet composition, hepatosomatic, and carcass percentage Affected the monounsaturated fatty acid profile of the fillet.	Samuelsena et al. (2001)
Phytase (500 or 1000 units/kg) supplemented in diet with 50% phosphorus content	Systematically, catalyzes the conversion of phytic acid to reduced phosphorylated myo-inositol (hydrolysis) derivatives and inorganic phosphate	Nile tilapia	Increased body weight and whole-body composition efficient in nutrient utilization	
Dietary phytase supplementation		Japanese seabass	Enhanced carcass phosphorus, carcass zinc, and carcass calcium Reduced total phosphorus effluent.	Ai et al. (2007)
Exogenous phytase and xylanase supplementation of fermented DORB (fermented by Rhizopus oryzae) based diet		Rohu	Growth performance in fish was less significant as compared to the only enzyme-supplemented DORB-based diets	Ranjan et al. (2021)

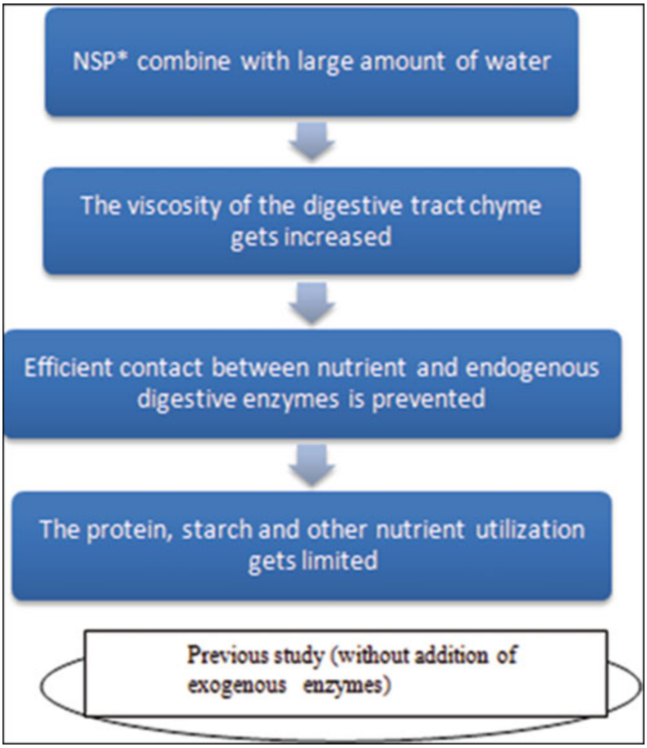

Fig. 1 Improvement in digestibility and utilization of feed

plant-based feedstuffs possess about 60–80% phosphorus (i.e. 600–800 g/kg) as phytate phosphorus forms. As the enzyme hydrolyzes the phytate phosphorus is absent in the fishes, henceforth, the phytate in combination with the phosphorus cannot be absorbed and utilized by the fish which in turn may pollute the water by releasing phosphorus. The administration of the respective exogenous enzymes (e.g. phytase for phytic acid) may cleave the phytic acid combined phosphorus to available phosphorus of fish, thereby inducing phosphorus utilization in the body of fish.

Influencing better growth performance and optimizing composition of the whole body: When formulated feeds are supplemented to the fish, the lack of significant enzymatic activity due to partial development in the digestive tract led to deteriorated growth performance as observed subsequently by Kolkovski et al. (1993). Therefore the digestive tract needs to be developed for a better enzymatic activity to improve the digestibility of the fish. One promising strategy is the incorporation of exogenous enzymes. The inclusion of exogenous enzymes appropriately can augment the deficient endogenous enzymes to improve the growth performance (Fig. 3).

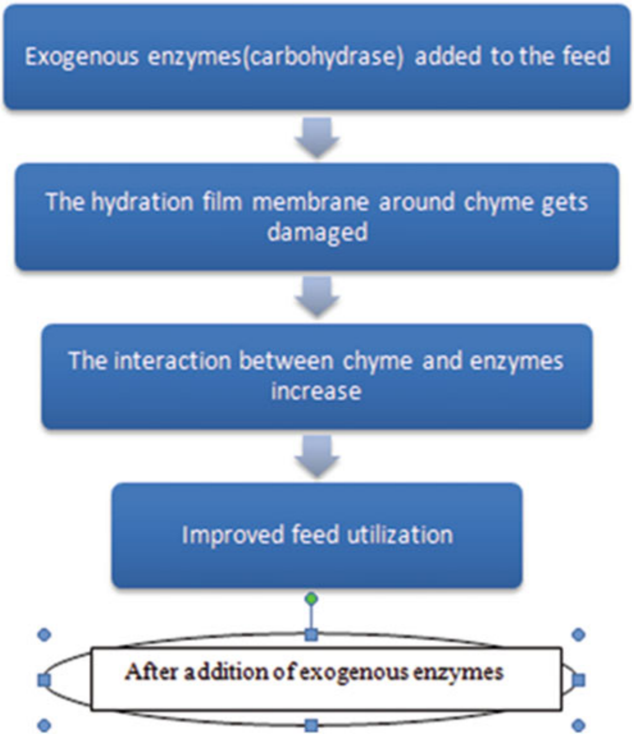

Fig. 2 Improvement in digestibility and utilization of feed

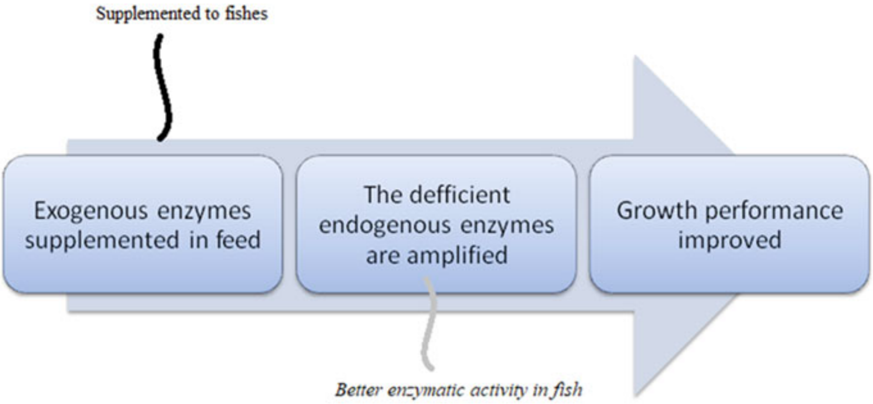

Fig. 3 Schematic presentation of inclusion of exogenous enzymes to improve growth performance

Immunity enhancement and resisting pathogens: The factors affecting the immune system in fish include pollution, pathogens, disease outbreak, stress, and feed (Doan et al. 2019). In a recent report, it was cited that a high WBC count had

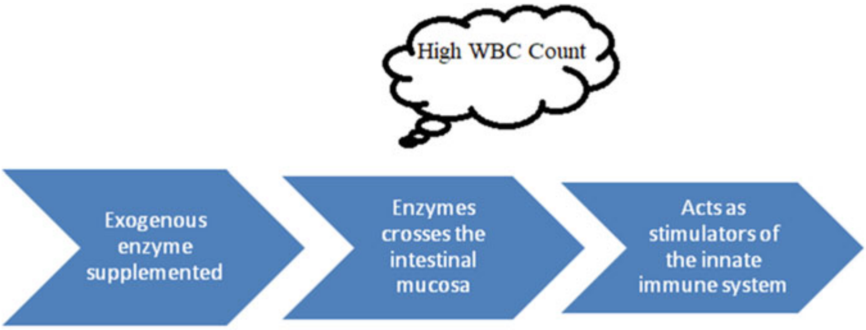

Fig. 4 Schematic presentation of exogenous enzyme inclusion to enhance immunity and resist pathogens

been observed in the enzyme-incorporated DORB-based diet with the inclusion level of xylanase being 16,000 U/kg and that of phytase being 500 U/kg (Ranjan et al. 2021; Fig. 4). Concerning the same, Zamini et al. (2014) reported that the supplementation of exogenous multienzyme in *Salmo trutta caspius* stimulated the innate immune system.

In lipid-based low-protein diets when lipase is supplemented in the diet the fish immune response was observed to be improved due to partial optimization of the acid phosphatase activity and complement protein followed by reduced pro-inflammatory cytokine gene expression by enhancing antibacterial peptides and anti-inflammatory cytokine gene expression, thereby partially regulating nuclear factor kBp65 protein inhibitors, kBa, intestinal kinase and rapamycin target signaling in fish (Liu et al. 2016).

Additionally, the changes in the composition of the diet also affect the gut microflora and fishes cannot respond to most plant-based diets due to the antinutritional factors and their inability to produce adequate enzymes required for the digestion of respective feedstuffs. The implementation of exogenous enzymes in the diet hydrolyzes the enzyme activity, thereby enhancing its digestibility. A study on grass carp fed with a cellulose-supplemented duckweed diet showed a significant change in the intestinal microbiota (Zhou et al. 2013).

4.2 Dietary Antioxidant Compounds in Fish Feed

Antioxidants are substances that keep molecules from oxidizing by inhibiting the generation of free radicals or interrupting their spread through the processes listed below: (1) collecting oxidizing species, (2) quelling metallic ions capable of creating reactive species, (3) preventing the chain reaction of auto-oxidation, and (4) lowering the concentration of focalized oxygen (Yabuta et al. 2010). Oxidative stress is described as damage to cells or tissues induced by an excess of oxidative chemicals, notably free radicals, with reactive oxygen species (ROS) being the most prominent.

Damage might result from an imbalance of pro-oxidant forces and antioxidants in favor of the former, a deficiency in the enzymatic antioxidant systems, or both (Liu et al. 2008) (Table 3).

4.3 Mixed Feeding Schedule

Farmers frequently utilize the feeding approach of feeding just below satiation. Farmers have noticed that on some days, fish eat all of the feed supplied to them, but on other days, they leave some feed uneaten. The link between feed intake, growth, and FCR is depicted schematically in Fig. 5. FCR diminishes until the fish are fed at a rate that is optimal for them. At the highest feeding rates, feed intake, and thus growth, begin to fluctuate, and FCR begins to exhibit an increasing tendency. When fish are fed more than their optimal feed intake, waste begins to accumulate.

Meal at just below satiation or developing diverse feeding patterns are two options for dealing with feed intake variation. Feeding at slightly below satiation necessitates a time-consuming weekly or biweekly satiation feeding level determination. De Silva (1985) proposed a mixed feeding schedule in which 30 percent protein and 18% protein diets were alternated, resulting in better nutritional utilization.

Xavier et al. (2016) conducted an experiment on mixed feeding schedules in rohu (*Labeo rohita*) where the fingerlings were fed different diets over 28 days, with either 28 days of diet D1 (100 g protein kg1 diet) or that of diet D2 (300 g protein kg1 diet) or 21 days of diet D1 (100 g protein kg1 diet) and 7 days of diet D2 (300 g protein kg1 diet), D3 (350 g protein kg1 diet), or D4 (400 g protein kg1 diet). T1 (D1 fed for 28 days), T2 (D2 fed for 28 days), T3 (D1 for 21 days and D2 for 7 days), T4 (D1 for 21 days and D3 for 7 days), or T5 (D1 for 21 days and D4 for 7 days) were the different treatments during this period and found that the nutrient utilization and growth performance parameters indicated that fingerlings fed a low-protein diet (D1) for 21 days followed by a normal-protein diet (D2) for 7 days in a 28-day cycle for 84 days maintained superior growth and health.

The results of this study demonstrated that varied feeding regimens influenced weight increase (percent), SGR, FCR, PER, and ANPU. The T3 group, which was fed a 100 g protein kg1 diet for 21 days and then a 300 g protein kg1 diet for 7 days, had the best growth performance, which was comparable to the T2 group fed a 300 g protein kg1 diet daily. The rate of fish growth was not accelerated when T4 and T5 were fed high-protein diets. This conclusion could be related to the fact that each fish has a protein limit beyond which additional protein cannot be successfully utilized (Wilson 1986; Ahmad et al. 2004; Debnath et al. 2007). These findings could be because protein deposition accounts for the majority of weight gain, and protein accretion is a balance of protein anabolism and catabolism. When compared to continuous feeding with low-protein diets, FCR and PER values were lower when fed high-protein diets and various mixed feeding schedules, according to Hossain et al. (2006). Indian main and common carps showed similar tendencies (Srikanth et al. 1988; Nandeesha et al. 1993, 1995). As evidenced by the ANPU number, this

Table 3 Studies on dietary antioxidant compounds in fish diet

Antioxidant compounds in the feed	Experimental fish	Cause of stress	Effective dose	Effects	References
α-Tocopherol in fish meal	*Clarias gariepinus*	Oxidative stress caused by deltamethrin		MDA levels and catalase activity ↑	Amin and Hashem (2012)
Tocopherol in combination with ascorbic acid (AA), iron, and selenium	*Oncorhynchus tshawytschaw albaum*	Oxidative stress	350 mg kg^{-1}	Reduction in oxidative stress	Welker and Congleton (2009)
β-Carotene, astaxanthin, and a mix of them	*Hyphessobrycon eques*	Stress caused by NH_4^+	10 mg kg^{-1}	Efficient enough to reduce the stress caused by ammonia	Fu et al. (2011)
Vitamin E	Hybrid tilapia (*Oreochromis niloticus x Oreochromis aureus*)	LPO in muscle and liver	64 IU kg^{-1}	Enough to maintain the levels of LPO close to the basal state in the analyzed tissues	Huang and Huang (2004)
Vitamin E	Crab	Microcystins		Antioxidant concentration in the tissue ↑ results in an effectual decrease in catalase activity	Pinho et al. (2005)
Garlic	Rainbow trout	Lipoperoxide (LPO) and catalase activity		↓ in the LPO value after the treatment	Mohebbi et al. (2012)
Lycopene	Nile tilapia	Cortisol and stress by overcrowding		Reduces the level of cortisol and keeps the enzymatic activities under control	Girao et al. (2012)
Interaction of selenium and vitamin E	*Oncorhynchus mykiss*	Oxidative stress		The concentration of selenium, immunity indicators, and enzyme activity of the oxidative stress increased significantly	Dantagnan et al. (2013)
Arachidonic acid (ARA)	*Salmo salar*	Oxidative stress and accumulation of ARA in liver		Significant reduction in catalase activity	Raatz et al. (2013)

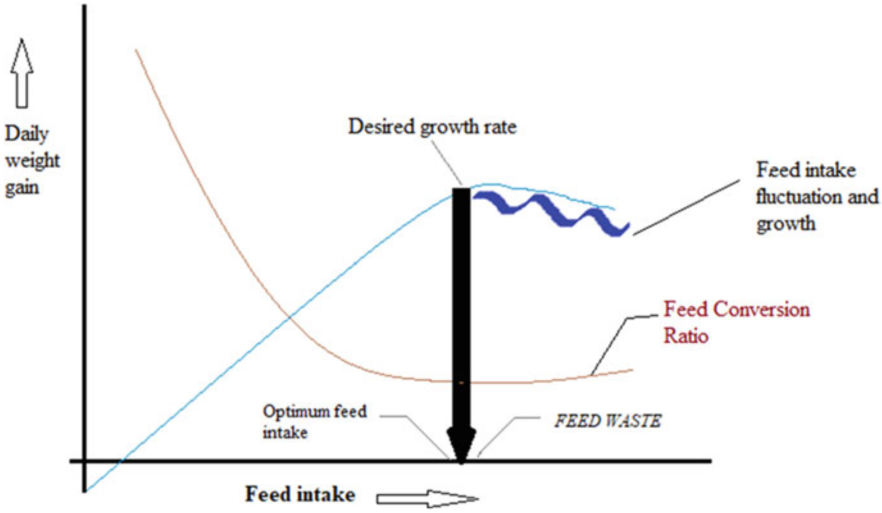

Fig. 5 Graphical presentation of feed input and growth of particular sized fish

shows that nutrient utilization was similar in both the T2 and T3 groups. The T3 group, however, had a higher PER value. This is due to the T3 group receiving less protein than the T2 group. In feeding schedules T4 and T5, both PER and ANPU significantly dropped as the protein level increased. This shows that at higher inclusion levels, protein consumption was lower. FCR and PER values were lower when fish were fed a high-protein diet, according to Hossain et al. (2006), and the efficiency with which fish convert dietary protein into tissue growth diminishes as the protein content of feed increases (Kumar et al. 2013). In the same group, stress indicator measures such as hyperglycemia and cortisol also contribute to improved immunity. This means that eating a high-protein diet daily is unnecessary because a species' protein need is an average value across time. As a result, adopting a specific feeding strategy that involves providing varied protein over a short period is likely to meet the requirement. The survival rates were similar in all groups, and the proximate composition was unaffected by the above technique, demonstrating that feeding a low-protein diet followed by a normal-protein diet is an effective strategy for lowering production costs.

5 Nutritional Programming

The recognized benefits of fish meal on human health, as well as its use, even if in tiny amounts, in other livestock production systems, have increased demand for this basic material, resulting in higher pricing. Aquatic feeds made from plants have shown to be less expensive, but the antinutritional effects make economic control difficult. Even while adding exogenous enzymes to food, fermenting it with helpful microbes, and employing probiotics are all useful, the cost of implementation ends up being a disadvantage. However, the prospective application lies in nutritional programming. Earlier, studies related to nutritional programming were carried out using models of mammals which showed that there is a strong interdependence between the nutrition gained during the early stages of life and its susceptibility to metabolic infirmities likely deterioration in growth permanently including nervous dysfunction and pathways associated with metabolism. This nutritional programming, evidently an innovative concept has set its foot in the domain of fisheries studies as well. Though the maternal metabolic programming and its generative processes between fishes and mammals are highly contrasting, early nutrition of fishes from both endogenous (maternally derived) and exogenous (larval feeding) sources could induce similar programming effects on development and metabolism. The effects of programming documented in fishes are based on survival, growth, brain development, and nutrient metabolism. The intervention of these effects can be brought out by utilizing varied byways of metabolism succeeded by inherited gene expression and its regulation during its flexible stages of development. Thus, nutritional programming could be brought into play as a strategy in aquaculture, thereby promoting sustainability in feeding trials.

5.1 Concept of Nutritional Programming

Nutritional programming (Fig. 6) also called metabolic programming is mostly studied for getting a successful outcome ignoring the cause of the study. Other

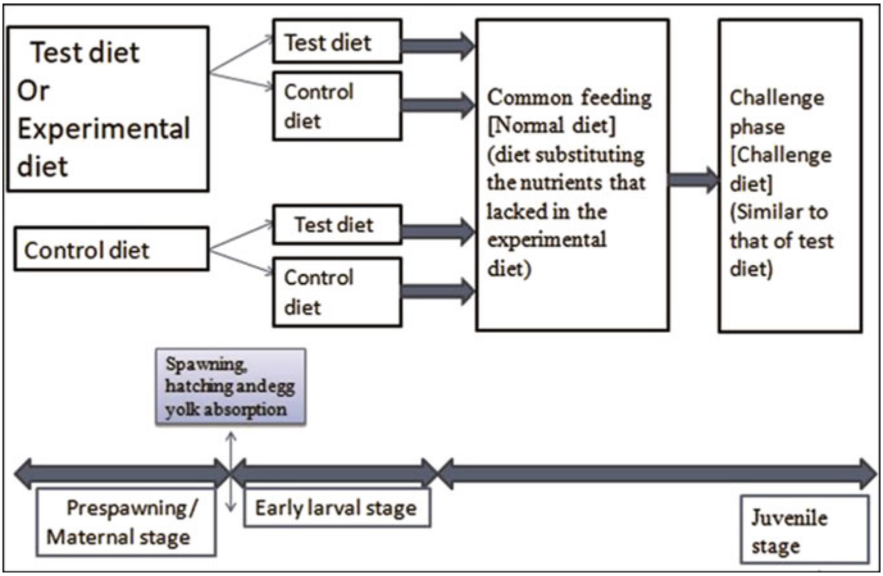

Fig. 6 The procedure followed in the nutritional programming of fishes

relevant terms for nutritional programming include fetal programming, focusing on vertical transmission between mother and daughter/son, or developmental programming associated with regenerative processes. The concept of nutritional programming involves two different types of maternal diets likely the control diet and the low-protein diet during pre-spawning and early larval stages. The shoal of fishes was cross-fostered at the time of spawning, thus producing two pairs of nutritional treatment groups for the offspring, i.e. control, low-protein diet during pre-spawning and early larval stages, post-spawning low-protein (only during post-spawning phase) pre-spawning low protein. By cross-fostering, one can investigate whether programming works for the pre-spawning or larval period or both and whether the programming effect is reversible. Following that, after certain cross-fostering investigations, a challenging experiment was done to see if nutritional programming increases adaptability to nutritionally inadequate settings. Following that, the fish on the experimental diet is switched to a "normal" diet for several weeks to months (which means an ideal diet, high-quality food, or a diet that replaces the nutrients that were missing in the experimental diet and is referred to as "common feeding"). The experimental or similar food is then administered (referred to as the "challenge diet") and is then rejected at the end of the "challenge phase." A common feeding period portrayed a benchmark for establishing if a study examined the effects of nutritional programming after the early dietary stimuli were withdrawn. A crossover feeding paradigm (the equivalent of cross-fostering) is not required.

5.2 The Benefits of the Study of Nutritional Programming Mechanisms using Fish as a Model

Because of their high batch fecundity, obtaining a large sample size with the same genotype is simple.

External embryonic development and organogenesis provide for greater access to the developing animal and better environmental control.

Quantification and assessment of the nutrients in the fish eggs are easier (Table 4).

Table 4 Nutritional programming studies in fish

Species	Programming window	Effects	Nutritional stimulus	References
Atlantic cod	Larval feeding	Growth	Copepod	Imsland et al. (2006), Koedijk et al. (2010), Øie et al. (2017)
	Larval feeding	Stress tolerance	Copepod	Øie et al. (2017)
Rainbow trout	Larval feeding	Growth, muscle growth	High fat	Alami-Durante et al. (2014)
	Larval feeding	Carbohydrate metabolism	Hyperglucidic +hypoxia	Liu et al. (2017), Hu et al. (2018)
	Larval feeding	Carbohydrate metabolism	Hyperglucidic	Geurden et al. (2007, 2014)
	Before spawning	Growth, survival; ingestion	Methyl group donor	Fontagne´-Dicharry et al. (2017)
	Before spawning	Lipid metabolism; carbohydrate metabolism	Methyl group donor	Seiliez et al. (2017)
	Adult life cycle	Lipid metabolism; carbohydrate metabolism; muscle growth	Plant-based diet	Lazzarotto et al. (2016)
	Larval feeding	Ingestion	Plant based diet	Geurden et al. (2013)
	Larval feeding	Growth	Plant-based diet	Geurden et al. (2013), Clarkson et al. (2017)
	Larval feeding	Lipid metabolism; muscle metabolism	Vitamin supplementation	Panserat et al. (2017)
European seabass	Larval feeding	Lipid metabolism	HUFA deficiency	Vagner et al. (2007, 2009)
	Larval feeding	Growth	Hyperglucidic	Zambonino-Infante et al. (2019)
	Larval feeding	Stress tolerance	Hyperglucidic	Zambonino-Infante et al. (2019)
	Larval feeding	Hypoxia tolerance	Hyperglucidic	Zambonino-Infante et al. (2019)
	Larval feeding	Carbohydrate metabolism	Hyperglucidic	Zambonino-Infante et al. (2019)
Gilthead seabream	Larval feeding	Carbohydrate metabolism	Hyperglucidic	Gong et al. (2015)
	Spawning	Growth; lipid metabolism	Plant-based diet	Izquierdo et al. (2015), Turkmen et al. (2017)
	Larval feeding	Growth; digestion	Plant-based diet	Perera and Yúfera (2016)

(continued)

Table 4 (continued)

Species	Programming window	Effects	Nutritional stimulus	References
	Larval feeding;	Inflammation	Plant-based diet	Perera and Yúfera (2016)
	Juvenile	Lipid metabolism, growth	Plant-based diet	Turkmen et al. (2017)
Zebrafish	Embryonic stage	Carbohydrate metabolism	Hyperglucidic	Rocha et al. (2014, 2015)
	Larval feeding	Carbohydrate metabolism	Hyperglucidic	Rocha et al. (2016a, b)
	Adult life cycle	Lipid metabolism	Maternal one-carbon micronutrient deficiency	Skjærven et al. (2016, 2018)
	Adult life cycle	Lipid metabolism	Maternal high ARA	Adam et al. (2018, 2019)
	Larval feeding	Inflammation	Plant-based diet	Perera and Yúfera (2016)
Senegalese sole	Larval feeding	Growth	Intact protein (vs hydrolysate with polypeptides)	Canada et al. (2018)
	Spawning	Growth, development (deformity); lipid metabolism	Maternal PUFA and vitamin supplementation	Morais et al. (2014)

6 Conclusion

By enhancing aquaculture system resilience, altering feed formulation and mixed feeding schedules with possible components and functional additives as well as innovative strategies like nutritional programming, and minimizing waste generation, aquaculture systems' sensitivity to climate change can be decreased.

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References

Adam AC, Skjaerven KH, Whatmore P, Moren M, Lie KK (2018) Parental high dietary arachidonic acid levels modulated the hepatic transcriptome of adult zebrafish (Danio rerio) progeny. PLoS One 13(8):e0201278

Adam AC, Lie KK, Whatmore P, Jakt LM, Moren M, Skjærven KH (2019) Profiling DNA methylation patterns of zebrafish liver associated with parental high dietary arachidonic acid. PLoS One 14(8):e0220934

Ahmad A, Mahyam MI, Solahuddin AR, Jamaludin I (2004) A guide to make and set durable artificial reef fish aggregating devices (ARFADs) for coastal areas

Ai Q, Mai K, Zhang W, Xu W, Tan B, Zhang C, Li H (2007) Effects of exogenous enzymes (phytase, non-starch polysaccharide enzyme) in diets on growth, feed utilization, nitrogen and phosphorus excretion of Japanese seabass, Lateolabrax japonicus. Comp Biochem Physiol A Mol Integr Physiol 147(2):502–508

Akhtar MS, Pal AK, Sahu NP, Ciji A, Mahanta PC (2013) Thermal tolerance, oxygen consumption and haemato-biochemical variables of Tor putitora juveniles acclimated to five temperatures. Fish Physiol Biochem 39(6):1387–1398

Alami-Durante H, Cluzeaud M, Duval C, Maunas P, Girod-David V, Médale F (2014) Early decrease in dietary protein: energy ratio by fat addition and ontogenetic changes in muscle growth mechanisms of rainbow trout: short-and long-term effects. Br J Nutr 112(5):674–687

Ali AA, Mannan MA, Parween S (2007) Effect of urea and malathion on the freshwater prawn, Macrobrachium lamarrei (HM Edwards), vol 26. University Journal of Zoology, Rajshahi University, pp 107–108

Amin KA, Hashem KS (2012) Deltamethrin-induced oxidative stress and biochemical changes in tissues and blood of catfish (Clarias gariepinus): antioxidant defense and role of alpha-tocopherol. BMC Vet Res 8(1):1–8

Blois JL, Williams JW, Fitzpatrick MC, Jackson ST, Ferrier S (2013) Space can substitute for time in predicting climate-change effects on biodiversity. Proc Natl Acad Sci 110(23):9374–9379

Bullock AM, Coutts RR (1985) The impact of solar ultraviolet radiation upon the skin of rainbow trout, Salmo gairdneri Richardson, farmed at high altitude in Bolivia. J Fish Dis 8(3):263–272

Canada P, Engrola S, Mira S, Teodosio R, del Mar Yust M, Sousa V, Pedroche J, Fernandes JM, Conceicao LE, Valente LM (2018) Larval dietary protein complexity affects the regulation of muscle growth and the expression of DNA methyltransferases in Senegalese sole. Aquaculture 491:28–38

Cao L, Chen Y, Dong S, Hanson A, Huang B, Leadbitter D, Little DC, Pikitch EK, Qiu Y, Sadovy de Mitcheson Y, Sumaila UR (2017) Opportunity for marine fisheries reform in China. Proc Natl Acad Sci 114(3):435–442

Clarkson M, Migaud H, Metochis C, Vera LM, Leeming D, Tocher DR, Taylor JF (2017) Early nutritional intervention can improve utilisation of vegetable-based diets in diploid and triploid Atlantic salmon (Salmo salar L.). Br J Nutr 118(1):17–29

Coutant CC (1986) Thermal niches of striped bass. Sci Am 255(2):98–105

Dalsgaard J, Verlhac V, Hjermitslev NH, Ekmann KS, Fischer M, Klausen M, Pedersen PB (2012) Effects of exogenous enzymes on apparent nutrient digestibility in rainbow trout (Oncorhynchus mykiss) fed diets with high inclusion of plant-based protein. Anim Feed Sci Technol 171(2–4):181–191

Dantagnan P, Bórquez A, Pavez C, Hernández A (2013) Feeding ω-3 PUFA enriched rotifers to Galaxias maculatus (Jenyns, 1842) larvae reared at different salinity conditions: effects on growth parameters, survival and fatty acids profile. Lat Am J Aquat Res 41(3):404–411

Das T, Pal AK, Chakraborty SK, Manush SM, Sahu NP, Mukherjee SC (2005) Thermal tolerance, growth and oxygen consumption of Labeo rohita fry (Hamilton, 1822) acclimated to four temperatures. J Therm Biol 30(5):378–383

Debnath D, Pal AK, Sahu NP, Baruah K, Yengkokpam S, Das T, Manush SM (2006) Thermal tolerance and metabolic activity of yellowtail catfish Pangasius pangasius (Hamilton) advanced fingerlings with emphasis on their culture potential. Aquaculture 258(1–4):606–610

Debnath D, Pal AK, Sahu NP, Yengkokpam S, Baruah K, Choudhury D, Venkateshwarlu G (2007) Digestive enzymes and metabolic profile of Labeo rohita fingerlings fed diets with different crude protein levels. Comp Biochem Physiol B: Biochem Mol Biol 146(1):107–114

Dell'Apa A, Johnson JC, Kimmel DG, Rulifson RA (2013) The international trade and fishery management of spiny dogfish: a social network approach. Ocean Coast Manag 80:65–72

De Silva SS (1985) Performance of Oreochromis niloticus (L.) fry maintained on mixed feeding schedules of differing protein content. Aquac Res 16(4):331–340

De Stasio Jr BT, Hill DK, Kleinhans JM, Nibbelink NP, Magnuson JJ (1996) Potential effects of global climate change on small north-temperate lakes: physics, fish, and plankton. Limnol Oceanogr 41(5):1136–1149

Diógenes AF, Castro C, Miranda AC, Oliva-Teles A, Peres H (2018) Dietary replacement of fishmeal by corn distillers dried grains with solubles (DDGS) in diets for turbot (Scophthalmus maximus, Linneaus, 1758) Juveniles. Aquaculture 492:113–122

Doan VH, Hoseinifar SH, Naraballobh W, Jaturasitha S, Tongsiri S, Chitmanat C, Ringø E (2019) Dietary inclusion of Orange peels derived pectin and Lactobacillus plantarum for Nile tilapia (Oreochromis niloticus) cultured under indoor biofloc systems. Aquaculture 508:98–105

Drew MD, Racz VJ, Gauthier R, Thiessen DL (2005) Effect of adding protease to coextruded flax: pea or canola: pea products on nutrient digestibility and growth performance of rainbow trout (Oncorhynchus mykiss). Anim Feed Sci Technol 119:117–128

FAO (2020) The state of world's fisheries and aquaculture. FAO, Rome

Felix N, Selvaraj S (2004) Enzymes for sustainable aquaculture. Aquaculture Asia 9:5–6

Fontagné-Dicharry S, Alami-Durante H, Aragão C, Kaushik SJ, Geurden I (2017) Parental and early-feeding effects of dietary methionine in rainbow trout (Oncorhynchus mykiss). Aquaculture 469:16–27

Fry JP, Love DC, MacDonald GK, West PC, Engstrom PM, Nachman KE, Lawrence RS (2016) Environmental health impacts of feeding crops to farmed fish. Environ Int 91:201–214

Fu H, Xie B, Ma S, Zhu X, Fan G, Pan S (2011) Evaluation of antioxidant activities of principal carotenoids available in water spinach (Ipomoea aquatica). J Food Compos Anal 24(2):288–297

Geurden I, Aramendi M, Zambonino-Infante J, Panserat S (2007) Early feeding of carnivorous rainbow trout (Oncorhynchus mykiss) with a hyperglucidic diet during a short period: effect on dietary glucose utilization in juveniles. Am J Phys Regul Integr Comp Phys 292(6):R2275–R2283

Geurden I, Borchert P, Balasubramanian MN, Schrama JW, Dupont-Nivet M, Quillet E, Kaushik SJ, Panserat S, Médale F (2013) The positive impact of the early-feeding of a plant-based diet on its future acceptance and utilisation in rainbow trout. PLoS One 8(12):e83162

Geurden I, Mennigen J, Plagnes-Juan E, Veron V, Cerezo T, Mazurais D, Zambonino-Infante J, Gatesoupe J, Skiba-Cassy S, Panserat S (2014) High or low dietary carbohydrate: protein ratios during first-feeding affect glucose metabolism and intestinal microbiota in juvenile rainbow trout. J Exp Biol 217(19):3396–3406

Ghomi MR, Shahriari R, Langroudi HF, Nikoo M, von Elert E (2012) Effects of exogenous dietary enzyme on growth, body composition, and fatty acid profiles of cultured great sturgeon Huso huso fingerlings. Aquac Int 20(2):249–254

Girao PM, Pereira da Silva EM, de Melo MP (2012) Dietary lycopene supplementation on Nile Tilapia (Oreochromis niloticus) juveniles submitted to confinement: effects on cortisol level and antioxidant response. Aquac Res 43(5):789–798

Gong G, Xue M, Wang J, Wu XF, Zheng YH, Han F, Liang XF, Su XO (2015) The regulation of gluconeogenesis in the Siberian sturgeon (Acipenser baerii) affected later in life by a short-term high-glucose programming during early life. Aquaculture 436:127–136

Häder DP, Kumar HD, Smith RC, Worrest R (2007) Effects of solar UV radiation on aquatic ecosystems and interactions with climate change. Photochem Photobiol Sci 6(3):267–285

Harrod C (2015) Climate change and freshwater fisheries. Freshwat Fish Ecol:641–694

Hayden B, Holopainen T, Amundsen PA, Eloranta AP, Knudsen R, Praebel K, Kahilainen KK (2013) Interactions between invading benthivorous fish and native whitefish in subarctic lakes. Freshw Biol 58(6):1234–1250

Hossain MA, Ali MZ, Rahman MM, Kader MA (2006) Evaluation of mixed-feeding schedules with varying dietary protein content on the growth performance and reduction of cost of production for sutchi catfish, Pangasius hypophthalmus (Sauvage) with silver carp, Hypophthalmichthys molitrix (Valenciennes). J Appl Aquac 18(1):63–78

Hu H, Liu J, Plagnes-Juan E, Herman A, Leguen I, Goardon L, Geurden I, Panserat S, Marandel L (2018) Programming of the glucose metabolism in rainbow trout juveniles after chronic hypoxia at hatching stage combined with a high dietary carbohydrate: protein ratios intake at first-feeding. Aquaculture 488:1–8

Huang CH, Huang SL (2004) Effect of dietary vitamin E on growth, tissue lipid peroxidation, and liver glutathione level of juvenile hybrid tilapia, Oreochromis niloticus× O. aureus, fed oxidized oil. Aquaculture 237(1–4):381–389

Imsland AK, Foss A, Koedijk R, Folkvord A, Stefansson SO, Jonassen TM (2006) Short-and long-term differences in growth, feed conversion efficiency and deformities in juvenile Atlantic cod (Gadus morhua) startfed on rotifers or zooplankton. Aquac Res 37(10):1015–1027

Islam MM, Khan MI, Barman A (2021) Impact of novel coronavirus pandemic on aquaculture and fisheries in developing countries and sustainable recovery plans: case of Bangladesh. Mar Policy 131:104611

Izquierdo MS, Turkmen SERHAT, Montero D, Zamorano MJ, Afonso JM, Karalazos V, Fernández-Palacios H (2015) Nutritional programming through broodstock diets to improve utilization of very low fishmeal and fish oil diets in gilthead sea bream. Aquaculture 449:18–26

Jeppesen E, Moss B, Bennion H, Carvalho L, De Meester L, Feuchtmayr H, Friberg N, Gessner MO, Hefting M, Lauridsen TL et al (2010) Interaction of climate change and eutrophication. In: Kernan M, Battarbee RW, Moss B (eds) Climate change impacts on freshwater ecosystems. Chichester (UK), Wiley-Blackwell, pp 119–151

Kandu P (2017) Papua New Guinea. Impacts of climate variations on local fisheries and aquaculture resources in PNG. In: Ramos EJ (ed) Ecological risk assessment of impacts of climate change on fisheries and aquaculture resources, vol 45. APEC Ocean and Fisheries Working Group, Peru, p 49

Kausar R, Salim M (2006) Effect of water temperature on the growth performance and feed conversion ratio of Labeo rohita. Pak Vet J 26(3):105–108

Koedijk RM, Folkvord A, Foss A, Pittman K, Stefansson SO, Handeland S, Imsland AK (2010) The influence of first-feeding diet on the Atlantic cod Gadus morhua phenotype: survival, development and long-term consequences for growth. J Fish Biol 77(1):1–19

Kolkovski S, Tandler A, Kissil GW, Gertler A (1993) The effect of dietary exogenous digestive enzymes on ingestion, assimilation, growth and survival of gilthead seabream (Sparus aurata, Sparidae, Linnaeus) larvae. Fish Physiol Biochem 12(3):203–209

Kumar S, Sahu NP, Pal AK, Choudhury D, Mukherjee SC (2006) Studies on digestibility and digestive enzyme activities in Labeo rohita (Hamilton) juveniles: effect of microbial α-amylase supplementation in non-gelatinized or gelatinized corn-based diet at two protein levels. Fish Physiol Biochem 32(3):209–220

Kumar S, Sahu NP, Pal AK, Sagar V, Sinha AK, Baruah K (2009) Modulation of key metabolic enzyme of Labeo rohita (Hamilton) juvenile: effect of dietary starch type, protein level and exogenous α-amylase in the diet. Fish Physiol Biochem 35:301–315

Kumar S, Sahu NP, Pal AK, Saravanan S, Priyadarshi H (2013) Short-term exposure to higher temperature triggers the metabolic enzyme activities and growth of fish Labeo rohita fed with high-protein diet. Aquac Nutr 19(2):186–198

Lappalainen J, Tarkan AS, Harrod C (2008) A meta-analysis of latitudinal variations in life-history traits of roach, Rutilus rutilus, over its geographical range: linear or non-linear relationships? Freshw Biol 53(8):1491–1501

Lazzarotto V, Corraze G, Larroquet L, Mazurais D, Médale F (2016) Does broodstock nutritional history affect the response of progeny to different first-feeding diets? A whole-body transcriptomic study of rainbow trout alevins. Br J Nutr 115(12):2079–2092

Liu H, Qiu N, Ding H, Yao R (2008) Polyphenols contents and antioxidant capacity of 68 Chinese herbals suitable for medical or food uses. Food Res Int 41(4):363–370

Liu S, Feng L, Jiang WD, Liu Y, Jiang J, Wu P, Zeng YY, Xu SD, Kuang SY, Tang L, Tang WN (2016) Impact of exogenous lipase supplementation on growth, intestinal function, mucosal immune and physical barrier, and related signaling molecules mRNA expression of young grass carp (Ctenopharyngodon idella). Fish & Shellfish Immunol 55:88–105

Liu J, Dias K, Plagnes-Juan E, Veron V, Panserat S, Marandel L (2017) Long-term programming effect of embryonic hypoxia exposure and high-carbohydrate diet at first feeding on glucose metabolism in juvenile rainbow trout. J Exp Biol 220(20):3686–3694

Liu W, Wu JP, Li Z, Duan ZY, Wen H (2018) Effects of dietary coated protease on growth performance, feed utilization, nutrient apparent digestibility, intestinal and hepatopancreas structure in juvenile Gibel carp (Carassius auratus gibelio). Aquac Nutr 24(1):47–55

Madeira F, Tscharntke T, Elek Z, Kormann UG, Pons X, Rösch V, Samu F, Scherber C, Batáry P (2016) Spillover of arthropods from cropland to protected calcareous grassland–the neighbouring habitat matters. Agric Ecosyst Environ 235:127–133

Mohebbi A, Nematollahi A, Dorcheh EE, Asad FG (2012) Influence of dietary garlic (Allium sativum) on the antioxidative status of rainbow trout (Oncorhynchus mykiss). Aquac Res 43 (8):1184–1193

Morais S, Mendes AC, Castanheira MF, Coutinho J, Bandarra N, Dias J, Conceição LE, Pousão-Ferreira P (2014) New formulated diets for Solea senegalensis broodstock: effects of parental nutrition on biosynthesis of long-chain polyunsaturated fatty acids and performance of early larval stages and juvenile fish. Aquaculture 432:374–382

Myers BJ, Lynch AJ, Bunnell DB, Chu C, Falke JA, Kovach RP, Krabbenhoft TJ, Kwak TJ, Paukert CP (2017) Global synthesis of the documented and projected effects of climate change on inland fishes. Rev Fish Biol Fish 27(2):339–361

Nandeesha MC, De Silva SS, Krishnamurthy D (1993) Evaluation of mixed feeding schedules in two Indian major carps, catla (Catla catla) and rohu (Labeo rohita). In: Kaushik SJ, Luquet P (eds) Fish nutrition in practice. INRA, Biarritz, pp 753–765

Nandeesha MC, De Silva SS, Krishna Murthy D (1995) Use of mixed feeding schedules in fish culture: performance of common carp, Cyprinus carpio L., on plant and animal protein based diets. Aquac Res 26(3):161–166

Nowicki R, Heithaus M, Thomson J, Burkholder D, Gastrich K, Wirsing A (2019) Indirect legacy effects of an extreme climatic event on a marine mega faunal community. Ecol Monogr 89(3): e01365

Noyes PD, McElwee MK, Miller HD, Clark BW, Van Tiem LA, Walcott KC, Erwin KN, Levin ED (2009) The toxicology of climate change: environmental contaminants in a warming world. Environ Int 35(6):971–986

Øie G, Galloway T, Sørøy M, Holmvaag Hansen M, Norheim IA, Halseth CK, Almli M, Berg M, Gagnat MR, Wold PA, Attramadal K (2017) Effect of cultivated copepods (Acartia tonsa) in first-feeding of Atlantic cod (Gadus morhua) and ballan wrasse (Labrus bergylta) larvae. Aquac Nutr 23(1):3–17

Ohlberger J (2013) Climate warming and ectotherm body size–from individual physiology to community ecology. Funct Ecol 27(4):991–1001

Pankhurst NW, Munday PL (2011) Effects of climate change on fish reproduction and early life history stages. Mar Freshw Res 62(9):1015–1026

Panserat S, Marandel L, Geurden I, Veron V, Dias K, Plagnes-Juan E, Pegourié G, Arbenoits E, Santigosa E, Weber G, Trichet VV (2017) Muscle catabolic capacities and global hepatic epigenome are modified in juvenile rainbow trout fed different vitamin levels at first feeding. Aquaculture 468:515–523

Pattanaik DR, Mohapatra M, Srivastava AK, Kumar A (2017) Heat wave over India during summer 2015: an assessment of real time extended range forecast. Meteorog Atmos Phys 129(4):375–393

Perera E, Yúfera M (2016) Soybean meal and soy protein concentrate in early diet elicit different nutritional programming effects on juvenile zebrafish. Zebrafish 13(1):61–69

Pinho GLL, da Rosa CM, Maciel FE, Bianchini A, Yunes JS, Proença LADO, Monserrat JM (2005) Antioxidant responses after microcystin exposure in gills of an estuarine crab species pre-treated with vitamin E. Ecotoxicol Environ Saf 61(3):361–365

Pörtner HO, Peck MA (2010) Climate change effects on fishes and fisheries: towards a cause-and-effect understanding. J Fish Biol 77(8):1745–1779

Raatz SK, Rosenberger TA, Johnson LK, Wolters WW, Burr GS, Picklo MJ Sr (2013) Dose-dependent consumption of farmed Atlantic salmon (Salmo salar) increases plasma phospholipid n-3 fatty acids differentially. J Acad Nutr Diet 113(2):282–287

Ranjan A, Kumar S, Sahu NP, Jain KK, Deo AD (2021) Exogenous phytase and xylanase supplementation of formulated diets for rohu (Labeo rohita): impact on haematology, histology and IGF I gene expression. Fish Physiol Biochem 47(1):49–58

Reid GC (1997) Solar forcing of global climate change since the mid-17th century. Clim Chang 37 (2):391–405

Reist JD, Wrona FJ, Prowse TD, Power M, Dempson JB, Beamish RJ, King JR, Carmichael TJ, Sawatzky CD (2006) General effects of climate change on Arctic fishes and fish populations. AMBIO: J Hum Environ 35(7):370–380

Rocha F, Dias J, Engrola S, Gavaia P, Geurden I, Dinis MT, Panserat S (2014) Glucose overload in yolk has little effect on the long-term modulation of carbohydrate metabolic genes in zebrafish (Danio rerio). J Exp Biol 217(7):1139–1149

Rocha F, Dias J, Engrola S, Gavaia P, Geurden I, Dinis MT, Panserat S (2015) Glucose metabolism and gene expression in juvenile zebrafish (Danio rerio) challenged with a high carbohydrate diet: effects of an acute glucose stimulus during late embryonic life. Br J Nutr 113(3):403–413

Rocha F, Dias J, Geurden I, Dinis MT, Panserat S, Engrola S (2016a) High-glucose feeding of gilthead seabream (Sparus aurata) larvae: effects on molecular and metabolic pathways. Aquaculture 451:241–253

Rocha F, Dias J, Geurden I, Dinis MT, Panserat S, Engrola S (2016b) Dietary glucose stimulus at larval stage modifies the carbohydrate metabolic pathway in gilthead seabream (Sparus aurata) juveniles: an in vivo approach using 14C-starch. Comp Biochem Physiol A Mol Integr Physiol 201:189–199

Salinas S, Munch SB (2012) Thermal legacies: transgenerational effects of temperature on growth in a vertebrate. Ecol Lett 15(2):159–163

Samuelsena T, Isaksenb M, Mclean E (2001) Influence of dietary recombinant microbial lipase on performance and quality characteristics of rainbow trout. Oncorhynchus mykiss. Aquaculture 194(1):161–171

Schiedek D, Sundelin B, Readman JW, Macdonald RW (2007) Interactions between climate change and contaminants. Mar Pollut Bull 54(12):1845–1856

Schindler DW, Bayley SE, Parker BR, Beaty KG, Cruikshank DR, Fee EJ, Schindler EU, Stainton MP (1996) The effects of climatic warming on the properties of boreal lakes and streams at the Experimental Lakes Area, northwestern Ontario. Limnol Oceanogr 41(5):1004–1017

Seiliez I, Vélez EJ, Lutfi E, Dias K, Plagnes-Juan E, Marandel L, Panserat S, Geurden I, Skiba-Cassy S (2017) Eating for two: consequences of parental methionine nutrition on offspring metabolism in rainbow trout (Oncorhynchus mykiss). Aquaculture 471:80–91

Shi X, Luo Z, Chen F, Huang C, Zhu XM, Liu X (2017) Effects of dietary cellulase addition on growth performance, nutrient digestibility and digestive enzyme activities of juvenile crucian carp Carassius auratus. Aquac Nutr 23(3):618–628

Shuter BJ, Finstad AG, Helland IP, Zweimüller I, Hölker F (2012) The role of winter phenology in shaping the ecology of freshwater fish and their sensitivities to climate change. Aquat Sci 74 (4):637–657

Skjærven KH, Jakt LM, Dahl JA, Espe M, Aanes H, Hamre K, Fernandes JM (2016) Parental vitamin deficiency affects the embryonic gene expression of immune-, lipid transport-and apolipoprotein genes. Sci Rep 6(1):1–11

Skjærven KH, Jakt LM, Fernandes JM, Dahl JA, Adam AC, Klughammer J, Bock C, Espe M (2018) Parental micronutrient deficiency distorts liver DNA methylation and expression of lipid genes associated with a fatty-liver-like phenotype in offspring. Sci Rep 8(1):1–16

Srikanth GK, Nandeesha MC, Kesavanath P, Varghese TJ, Shetty HPC, Basavaraja N (1988) On the applicability of a mixed feeding schedule for common carp, Cyprinus carpio var. Communis. In: Aquacultural research in Asia: management techniques and nutrition, p 254

Turkmen S, Zamorano MJ, Fernández-Palacios H, Hernández-Cruz CM, Montero D, Robaina L, Izquierdo M (2017) Parental nutritional programming and a reminder during juvenile stage affect growth, lipid metabolism and utilisation in later developmental stages of a marine teleost, the gilthead sea bream (Sparus aurata). Br J Nutr 118(7):500–512

UNFAO (2014) Food and Agriculture Organization of the United Nations. UNFAO, Rome

Vagner M, Infante JZ, Robin JH, Person-Le Ruyet J (2007) Is it possible to influence European sea bass (Dicentrarchus labrax) juvenile metabolism by a nutritional conditioning during larval stage? Aquaculture 267(1–4):165–174

Vagner M, Robin JH, Zambonino-Infante JL, Tocher DR, Person-Le Ruyet J (2009) Ontogenic effects of early feeding of sea bass (Dicentrarchus labrax) larvae with a range of dietary n-3 highly unsaturated fatty acid levels on the functioning of polyunsaturated fatty acid desaturation pathways. Br J Nutr 101(10):1452–1462

Verma AK, Pal AK, Manush SM, Das T, Dalvi RS, Chandrachoodan PP, Ravi PM, Apte SK (2007) Persistent sub-lethal chlorine exposure elicits the temperature induced stress responses in Cyprinus carpio early fingerlings. Pestic Biochem Physiol 87(3):229–237

Warren DR, Robinson JM, Josephson DC, Sheldon DR, Kraft CE (2012) Elevated summer temperatures delay spawning and reduce redd construction for resident brook trout (S alvelinus fontinalis). Glob Chang Biol 18(6):1804–1811

Wedekind C, Kueng C (2010) Shift of spawning season and effects of climate warming on developmental stages of a grayling (Salmonidae). Conserv Biol 24(5):1418–1423

Wedemeyer GA, Meyer FP, Smith L (1999) Environmental stress and fish diseases. Narendra Publishing House, New Delhi, p 107

Welker TL, Congleton JL (2009) Effect of dietary α-tocopherol+ ascorbic acid, selenium, and iron on oxidative stress in sub-yearling Chinook salmon (Oncorhynchus tshawytscha Walbaum). J Anim Physiol Anim Nutr 93(1):15–25

Wilson RP (1986) Protein and amino acid requirements of fishes. Annu Rev Nutr 6:225–244

Wrona FJ, Prowse TD, Reist JD, Hobbie JE, Lévesque LM, Vincent WF (2006) Climate change effects on aquatic biota, ecosystem structure and function. AMBIO: J Hum Environ 35(7):359–369

Xavier B, Jain KK, Pal AK, Sahu NP, Maheswarudu G, Gal D, Kumar S (2016) Mixed feeding schedule of low and high protein in the diet of Labeo rohita (Hamilton) fingerlings: effect on growth performance, haemato-immunological and stress responses. Aquac Nutr 22(3):652–663

Yabuta Y, Fujimura H, Kwak CS, Enomoto T, Watanabe F (2010) Antioxidant activity of the phycoerythrobilin compound formed from a dried Korean purple laver (Porphyra sp.) during in vitro digestion. Food Sci Technol Res 16(4):347–352

Yigit NO, Olmez M (2011) Effects of cellulose addition to canola meal in tilapia (Oreochromis niloticus L.) diets. Aquac Nutr 17(2):e494–e500

Yildirim YB, Turan F (2010) Effects of exogenous enzyme supplementation in diets on growth and feed utilization in African catfish, Clarias gariepinus. J Anim Vet Adv 9(2):327–331

Zagarese HE, Williamson CE (2000) Impact of solar UV radiation on zooplankton and fish. Eff UV Radiat Mar Environ 10:279

Zambonino-Infante JL, Panserat S, Servili A, Mouchel O, Madec L, Mazurais D (2019) Nutritional programming by dietary carbohydrates in European sea bass larvae: not always what expected at juvenile stage. Aquaculture 501:441–447

Zamini AA, Kanani HG, Esmaeili AA, Ramezani S, Zoriezahra SJ (2014) Effect of two dietary exogenous multi-enzyme supplementation, Natuzyme® and beta-mannanase (Hemicell®), on growth and blood parameters of Caspian salmon (Salmo trutta caspius). Comp Clin Pathol 23 (1):187–192

Zheng CC, Wu JW, Jin ZH, Ye ZF, Yang S, Sun YQ, Fei H (2020) Exogenous enzymes as functional additives in finfish aquaculture. Aquac Nutr 26(2):213–224

Zhou Y, Yuan X, Liang XF, Fang L, Li J, Guo X, Bai X, He S (2013) Enhancement of growth and intestinal flora in grass carp: the effect of exogenous cellulase. Aquaculture 416:1–7

Zhou L, Limbu SM, Shen M, Zhai W, Qiao F, He A, Du ZY, Zhang M (2018) Environmental concentrations of antibiotics impair zebrafish gut health. Environ Pollut 235:245–254

Vulnerability and Mitigation Approach to Nutritional Pathology for Sustainable Fish Growth in Changing Climatic Conditions

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Abstract

Aquaculture represents a booming sector to augment human food and nutritional security. The changing face of the climate over the years has given a lesson for improvising the system and the nutritional aspects of the candidate fish species. Given this scenario, nutritional biotechnology approaches through the application of functional foods in aquafeed have a lot to do with the futuristic mitigation of climate-induced vulnerability and challenges. The physiological dysfunction, as seen through deficiency diseases/syndromes in fishes when stocked in the highly intensive system, is of grave concern to the farming community. Therefore, a precise understanding of the nutritional need of the species apart from the role of several functional foods in aquaculture is essential. Several functional foods in the forms of probiotics, prebiotics, synbiotics, vitamins, nutri-enzymes, etc. are available through a series of research on fish models. A prudent approach for its field-level application can guide us to tackle the climate-induced scenario for sustaining the growing aquaculture industry. In this context, the chapter provides a narrative account of the critical nutrient deficiency diseases and the functional role of dietary nutrients to tackle the scenario.

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Keywords

Climate change · Functional food · Nutritional deficiency · Probiotic · Prebiotic · Synbiotic

1 Introduction

Climate change is defined as variations in the statistical distribution of weather over an extended period, covering a longer duration ranging from decades to millions of years. Climate change is the most significant environmental challenge, and poses the biggest threat to global food security in the years to come. The climatic pattern around the globe is changing, and the frequency of weather events, mean surface and water temperatures are a growing concern for the existance of human race. The cause behind the current climatic change scenario is linked to the emission and increment of greenhouse gases in the atmosphere, leading to global warming. The perceived consequences of the changing climatic regime include extreme weather events that cause water shortage, resulting in failure of agricultural crops, warming and acidification of the ocean, sea-level rise, adverse changes in water quality, sedimentation, or rapid variation in salinity (D'Abramo and Slater 2019). The speculated impact of global climate change on the overall fisheries activities, including capture and culture-based industry, is expected to be extreme, and stringent action planning is required to tackle the changing face shortly.

The aquaculture industry, with a target for providing quality, cheap protein for the exploding human population, apart from livelihood security, is growing fast and is identified as a future sustainable food production sector. Of recent, the effect of climate change on aquaculture sustainability has received considerable interest because the sector contributes significantly to global food security, nutrition, and livelihoods. In this midst, the industry's further growth is greatly affected by the climate change scenario (Callaway et al. 2012). Fishes being a poikilothermic aquatic organism, their physiology, especially the metabolic and immune response, directly relates to the ambient water temperature (Bowden et al. 2007). Consequently, the frequent occurrence of extreme weather events will induce uncomfortable stress on aquatic organisms, which impacts their growth and productivity in the long run. Besides, the nexus between the host environment and the pathogen is likely to take a negative turn in events of a deteriorating water environment. It is well established that harmful pathogens that already exist in the system may trigger their pathogenicity with a change in the ambient temperature. Further, the temperature is considered a key determinant of the fish immune response, and the rapid multiplication of pathogens manifests probable outbreak of disease, and causes mortality. For example, rising water temperatures may favor the existing balance either towards the host or pathogen, which ultimately may change the occurrence and distribution of the disease. Therefore, it is highly likely that the effect of climate change may severely affect fish more than in earlier cases. The disease is a major concern for aquaculture in comparison to capture fisheries as the culture-based system is established in smaller confinement, coupled with a high stocking density that increases the chances for toxic metabolite accumulation (Walker and Mohan 2009). Further, there are concerns that the altering climate can further hasten the threats posed by diseases via changes in the prevalence, distribution, virulence of harmful pathogens, and alterations in host susceptibility (Harvell et al. 1999). Apart from this, the extreme weather condition, in combination with higher temperatures and other anthropogenic as well as environmental factors, is likely to degrade and alter fish habitat and water quality (Brander 2007).

Disease emergence is one of the key impediments to the progressive growth of aquaculture and its sustainability as the production cost will significantly increase on account of the investment cost for preventive, control, and treatment measures adopted. Apart from the severe disease emergence due to climatic instability, the case of nutritional disease occurrence is also likely to impact the industry. Nutritional diseases in fish develop as a consequence of deficiency (generally undernutrition), excess nutrition (overnutrition), or an imbalance (malnutrition) of available nutrients supplied via feed. The disease usually develops because the animals have body reserves that could frame the nutritional deficiency. At the same time, the disease establishes itself only when the amount of the dietary component reaches far below the critical level. Sometimes, it also happens that when there is excess food, the extra nutrient component is diverted as fat deposits in fish bodies and organs, which again may have a negative impact on the physiological functioning of the organism.

In short, climate change and the consequent global warming phenomenon have already impacted the efficiency and progress of the food production sector, including the aquaculture industry. Despite the technological advances made in the last few decades, most projections indicate that the entire aquaculture value chain is very much vulnerable to the subsequent effects of climate change. The outbreak of the disease, concomitant with the inadequate and unbalanced dietary formulation, will impact the growth and physiology of the cultured organisms. The chapter reviews the documented nutritional disease in fish with a special note on climate vulnerability, and further, an exercise is made to tackle the scenario through the biotechnological approaches.

2 Disease Caused by Pathogens

The occurrence, spread, and severity of disease in the aquaculture system are similar in respect to that of the terrestrial animal. Fish being an aquatic organism, the spread of disease mainly occurs via water. The occurrence of a disease does not happen from a simple contact of the fish with an invading pathogen. Here, the surrounding environmental situations like poor water quality, along with available stressors contribute to disease outbreaks. There exists a delicate balance between host, pathogen, and environment, and thus when the established homeostasis is disturbed, it causes stress in fishes, leading to disease. Stressors such as poor water quality, higher microbial load, nutritional deficiency, and high stocking density can often cause stress in fish and ultimately leads to the chances of infection by opportunistic

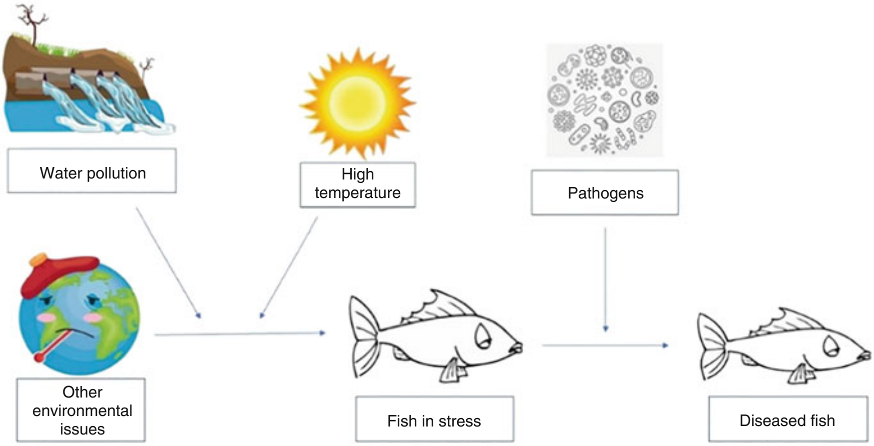

Fig. 1 Effect of different environmental issues on fish health

pathogens in the aquatic environment (Fig. 1). In general, disease occurrence in the fish can be broadly classified into two categories, viz. a. infectious and b. non-infectious diseases. Infectious disease is mainly contagious and caused by pathogenic organisms in the environment, whereas non-infectious diseases are mostly non-contagious and caused by several environmental factors, nutritional deficiencies, or genetic anomalies.

3 Infectious Disease in Aquaculture

Pathogenic groups, including bacteria, fungi, and virus, cause a wide array of infectious disease in the aquaculture system. In general, they are saprophytic in nature and become pathogenic when fishes are physiologically triggered, nutritionally deficient, or under stressed conditions (i.e., poor water quality, crowding), which allow these opportunistic pathogens to overcome, and attack the fish defense cascade, and further proceed to infections. Disease outbreaks can significantly hamper aquaculture production, and affect the economics of the culture system, eventually leading to massive economic losses. A narrative account of the common infectious fish diseases in fish is outlined in Table 1.

4 Nutritional Diseases

The most important aspect being considered while culturing fishes in captivity is to provide adequate nutrition, alongside a proper feeding management strategy. Malnourished or under-nourished animals are unable to maintain their health status and growth despite a suitable environment. Proteins, carbohydrates, lipids, vitamins, and minerals are important essential nutrients for the proper growth of fishes. Slow

Table 1 Common infectious diseases in Indian aquaculture

Sl no	Disease condition	Causative agent/ factor	Species affected	Symptoms
A. Parasitic diseases				
1	Argulosis (Carp lice)	*Argulus* spp.	Most freshwater fish species where scales are affected. *Labeo rohita* more susceptible	The parasite is visible on the skin surface, leading to skin lesions with secondary bacterial infections, hemorrhagic spots, and ulcers
2	Ichthyophthiriasis (Ich/White spot disease)	*Ichthyophthirius multifiliis*	Most freshwater fishes	White spots on fins, body surface, gills
3	Trichodiniasis	*Trichodina* spp.	Most fishes are vulnerable	Whitish cysts are visible on skin, fins, and gills. Disc-shaped, spherical whitish colored cysts can be observed under a microscope
4	Dactylogyrosis (gill fluke)	*Dactylogyrus*	All freshwater fishes	Predominantly affects gills, damages the gill filaments, gills with clumps of white masses are seen
5	Gyrodactylosis (Skin fluke)	*Gyrodactylus* spp.	All freshwater fishes	Grows on and damages the skin, gills which leads to clumps of white masses, frequently followed by secondary infections
6	Myxosporidiasis	*Myxosporidium* spp.	All freshwater fishes	Occurrence of cysts on different parts of the body, internal organs, and gill filaments, fish becomes lethargic, falling of scales, typical cysts can be observed in gill squash under microscope

(continued)

Table 1 (continued)

Sl no	Disease condition	Causative agent/ factor	Species affected	Symptoms
7	Lernaeosis	Anchor worm (*Lernae* spp.)		Small thread-like worm attaches to the body surface (fin), anorexia (poor growth), and irritation
B. Bacterial diseases				
1	Columnaris disease	*Flavobacterium columnare* (*Flexibacter/ Cytophaga columnaris*)	All freshwater fishes	Hemorrhagic and ulcerative lesions on fins, head, back of skin, which may observe as yellow to orange due to bacterial growth and pigmentation
2	Fin rot and tail rot	*A. hydrophila, Pseudomonas* spp. *Cytophaga* spp., *Haemophilus* spp.	All freshwater fishes	Erosions, discoloration, and disintegration of fins and tail
3	Gill rot or bacterial gill disease or environmental disease	*Flavobacterium branchiophilum, Cytophaga* spp., *Flexibacter* spp.	All freshwater fishes	Gasping of fish on water surface, lethargic, gills look discolored with trapped materials, followed by secondary fungal infection
4	Aeromoniasis or motile Aeromonas septicaemia	*Aeromonas hydrophila, A veronii. A. Sobria, A. sobria*	All freshwater fishes	Hemorrhagic and ulcerative lesions on head, fins, skin, exophthalmia
5	Edwardsiellosis or Edwardsiella septicaemia	*Edwardsiella tarda*	All freshwater and some brackish water fishes	Hemorrhagic ulcers on skin, fins, and body, ulcerative abscesses in internal organs, rectal protrusion
6	Vibriosis	*Vibrio anguillarum, V. parahaemolyticus, V. alginolyticus*	Freshwater prawn and shrimps	Hemorrhagic ulcers on skin, ulcerative abscesses in internal organs, fins, and body
7	Eye disease	*Aeromonas liquefaciens, Staphylococcus aureus, various other bacteria*	All freshwater fishes	Cataracts affect cornea, eyeball gets putrefied

(continued)

Table 1 (continued)

Sl no	Disease condition	Causative agent/ factor	Species affected	Symptoms
8	Pseudomoniasis/ Pseudomonas septicaemia	*Pseudomonas* sp. *Pseudomonas fluorescens*	Freshwater fishes and salt water fishes	Hemorrhagic lesions on skin, fins, tail
9	Enteric red mouth disease (ERM)	*Yersinia ruckeri*	Reported mainly in freshwater fish species, sturgeon, European eels, and carps, salmonids seem to be more sensitive to this bacterium	Hemorrhagic lesions on the surface skin especially around the mouth, fins, tail. Internal hemorrhages
C. Fungal diseases				
1	Saprolegniasis	*Saprolegnia parasitica*	All freshwater fishes	Fish becomes weak, ulceration of skin with hemorrhages, cotton wool growth on ulcers with gray patches
2	Branchiomycosis (Gill rot disease)	*Branchiomyces demigrans*	Most species of freshwater fishes	Fungi grow on decaying organic matter deposited at the pond bottom. Fish are lethargic and shows redness of gills initially, which further turns grayish-white, necrosis of gill filaments
3	Epizootic ulcerative syndrome (EUS)	*Aphanomyces invadans* sp. (fungus), *Aeromonas hydrophila, A. sobria*	Freshwater fishes	Fish become lethargic, redness of the skin, ulcerative patches, high mortality
D. Viral diseases				
1	White spot syndrome virus (WSSV)	Whispovirus (family Nimaviridae)	*Penaeus monodon, P. vannamei*	Loose carapace, high degree of color variation with a predominance of the darkened (red, brown, or pink) body surface and appendages, heavy fouling of the surface and gills by external parasites, white midgut line

(continued)

Table 1 (continued)

Sl no	Disease condition	Causative agent/ factor	Species affected	Symptoms
				through the abdomen of severely affected larvae and post-larvae, white calcium deposits embedded in the shell, causing white spots 0.5–3.0 mm in diameter
2	White tail disease (WTD) or white muscle disease (WMD)	Nodavirus (MrNV)	*Macrobrachium rosenbergii*	Lethargy, anorexia, and opaqueness of abdominal muscle in post-larvae. This opaqueness gradually expands on both sides (anterior and posterior) and leads to degeneration of telson and Uropods in severe cases
3	Koi herpesvirus disease (KHVD)	Cyprinid herpesvirus 3; CyHV3	Mostly seen in tropical and temperate regions; fishes like common carp and koi are the most susceptible species	Bleeding gills with severe lesions which exhibit as mottling with red and white patches, sunken eyes, and pale patches on the skin
4	Viral encephalopathy and retinopathy (VER) or viral nervous necrosis	Betanodavirus (Nodaviridae)	A serious disease of several marine fishes	Vacuolating necrosis in neural cells of brain, retina, and spinal cord. Severity is high, i.e., up to 100% mortality in young fishes)

Adapted from the list of common infectious diseases in Indian aquaculture (Mishra et al. 2017; Mallick and Panigrahi 2018)

growth rate, reduced fecundity, decreased appetite, increased vulnerability to diseases, lethargic with clinical signs, pathological lesions, and mortality are important symptoms of nutritional diseases. Most nutritional diseases are difficult to identify at early stages due to their chronic nature but can be mitigated through proper feeding management practices (Shefat and Karim 2018). Healthy farming conditions and a nutritionally balanced, and live/artificial diet are vital requirements for sustainable aquaculture production along with good health management that can prevent nutritional diseases in cultured fish species (Joseph and Raj 2002). In this context, it becomes imperative to understand and control various nutritional diseases to increase fish supply through aquaculture production. Highlighted below are some of the important dietary diseases in the context of protein, lipid, carbohydrates, vitamins, and minerals.

5 Protein Deficiency Diseases

Proteins are made up of a set of amino acids, which gives individual proteins a unique characteristic. Like any other animals, fish synthesize body proteins from amino acids available in the diet as well as from different sources. Based on the requirement of animals, the amino acids are classified as "essential" or "indispensable" amino acids and "non-essential" or "dispensable" amino acids. The animal can synthesize the "non-essential" amino acids. These dispensable amino acids may also be present in dietary protein and are used to synthesize body proteins. A deficiency of any one of the essential amino acids can impede protein synthesis, leading to reduced weight gain and other specific deficiency symptoms. Therefore, meeting the minimum dietary requirement of protein or a balanced amount of amino acids is critical for adequate growth, development, and health of a fish. However, higher protein levels in the diet are both economically and environmentally impractical because protein represents the most expensive dietary component in the fish feed. The excess protein in the diet increases the waste build-up and requires more energy to excrete nitrogenous waste. The maintenance, and growth of fish depends on both the quantity and quality of protein in the diet. This dependence becomes more crucial when fishes are under unfavorable conditions. For example, the deleterious effects of high stocking densities, water pollutants, hypoxia, and stress can be well tolerated by fish when on diets containing sufficient quantity and quality of protein. Protein is considered a crucial nutrient for the growth of fish to ensure the formation and activity of enzymes and hormones. Fishes require dietary protein as a source of amino acids for synthesis of protein and functioning of glycolytic pathway. The important feature determining protein quality for fish diet is the level and availability of the essential amino acid which can be effectively utilized by the fish. The deficiency of one or more of these amino acids can lead to diseases. Underutilization of dietary protein often leads to poor weight gain, growth retardation, low feed conversion efficiency, and lower resistance to diseases. As a result, diseases like scoliosis, lordosis, and anemia are reflected in fish. Lordosis is explained as an abnormal ventral curvature of the vertebral column, accompanied by abnormal calcification of the afflicted vertebrae, whereas scoliosis is considered as a congenital nutritional deficiency resulting in curvature of the dorsal spine (lateral) of fish. There are published reports of deficiency of amino acids like tryptophan that can cause scoliosis, lordosis (Walton et al. 1984) in *Oncorhynchus mykiss*, *O. nerka, O. keta*, *O. kisutch*. Conversely, methionine deficiency can cause lens cataracts (Poston et al.

1977) in *O. mykiss* and *Salmo salar*. Lysine deficiency can cause dorsal/caudal fin erosion (Walton et al. 1984; Ketola 1983) in *Oncorhynchus mykiss and Cyprinus carpio.*

6 Lipid Deficiency Diseases

Excess dietary fats, deficiency of fatty acids, and the toxic effect of unsaturated nutritional fats can cause pathological conditions in fish. The most common symptoms associated with lipid deficiency are reduced growth, fin erosion, skin depigmentation, rapid swimming followed by loss of reflex and immobility; fish may float or sink to the bottom and then recover or die. Simultaneously, excess intake of dietary fat can cause detrimental effects on fish (Table 2).

7 Carbohydrate Deficiency Diseases

Being an inexpensive source of energy in diets, fishes do not have a specific dietary requirement for carbohydrates. The ability to utilize dietary carbohydrates for energy varies with different fish species, wherein herbivorous and omnivorous species possess an effective capacity for its utilization as a source of energy compared to many carnivorous species (Wilson 1994). Carbohydrates are stored as glycogen in tissues, especially in liver and muscle tissues, serving as an instant energy source. A portion of the dietary carbohydrate is transformed to lipid, which further deposited as

Table 2 Nutritional diseases in fishes due to lipid deficiency

Sl. no	Lipid nutritional diseases	Causes	Symptoms
1	Lipidosis	Feeding of fatty or poorly stored, rancid formulated feed	Fishes mostly in the grow-out stage are most prone to lipidosis. Affected fish shows reduced growth, low mortality rate, opaque eyes, lethargic movement, slight distention of the abdomen, and pale appearance of liver
2	EFA deficiency	Associated with low levels of essential fatty acids in live food. Fatty acid deficiency results in larval mortality known as "shock syndrome"	Body weakness and mortality are the most common symptoms
3	Obesity	Fatty infiltration of liver, mostly correlated with a high-fat diet	Swollen pale liver, fatty liver
4	Nutritional myopathy	Associated with rancid fat or PUFA containing diets and low vitamin E contents	Body color darkening, emaciation, petechia at operculum, and occasional spinal cord deformity

(Adapted from Shefat and Karim 2018)

an energy store for future needs. Carbohydrate deficiency results in growth retardation as a result of gluconeogenesis pathway. Sekoke disease, also known as spontaneous diabetes, is a common disease related to carbohydrates in carps, arising probably due to excessive feeding with silkworm pupae in the diet. This leads to bilateral cataracts, degenerative changes in extrinsic eye muscle and retina.

8 Vitamin Deficiency Diseases

About 15 vitamins are essential for terrestrial animals and several fish species that have been examined to date (Halver 2002). In general vitamins are organic compounds which are needed in comparatively lesser quantities for supporting definite metabolic or structural functions. They are divided into two major groups depending on the solubility as (a) fat-soluble and (b) water-soluble vitamins. Examples of fat-soluble vitamins are vitamin A (retinol), vitamin D (cholecalciferol), vitamin E (alpha-tocopherol), and vitamin K. These vitamins are first metabolized and then accumulate along with body lipids and therefore enable fishes to survive for longer periods in the absence of fat-soluble vitamins. Water-soluble vitamins comprise ascorbic acid (vitamin C) and vitamin B complex. They cannot be stored in the body; thus, deficiency signs usually emerge within weeks in young and rapidly growing fishes. Most of these water-soluble vitamin functions as a component of coenzymes that have specific metabolic functions.

Usually, vitamin deficiency signs (Table 3) develop slowly, and it is quite difficult to detect the deficiency signs at the early stages. However, poor feeding efficiency, poor appetite, and reduced weight gain are some among the vitamin deficiency signs that can enable us to predict its deficiencies. The absence of a particular vitamin in the diet leads to serious metabolic disorders called *Avitaminosis* that can cause severe fatality. Higher deficiency of vitamins can cause non-specific growth retardation and can lead the fish susceptible to diseases (Imelda and Paulraj 2002). In this context, an optimum level of vitamin is necessary for the development of immunity especially in the early life stages of fishes (Joseph and Raj 2002). Under rare conditions, accumulation of water-soluble vitamins can produce a toxic condition which is called hypervitaminosis. These types of conditions will not arise during practical farming conditions.

9 Mineral Deficiency Diseases

Minerals are the inorganic elements needed for various functions. Minerals are vital for both aquatic and terrestrial animals for osmoregulation, tissue formation, and other key metabolic activities (Imelda and Paulraj 2002). Fish take minerals dissolved in water to meet some of their metabolic needs. Minerals are usually classified as (a) macro- or (b) microminerals, based on the amount needed in food, and are stored in the body. Macrominerals include calcium, phosphorus, magnesium, chloride, sodium, potassium, and sulfur. Dietary deficiencies of most macromineral do not occur in fishes since they are obtained in the form of ions from water via gills.

Table 3 Different vitamins and their deficiency signs in fishes (modified from Shefat and Karim 2018)

Vitamin	Deficiency symptoms
Thiamine-B1	Anorexia, poor appetite, loss of equilibrium, muscle atrophy poor growth, fading of body color, congestion of fins and skin, lethargy
Riboflavin-B2	Photophobia, eye and skin hemorrhage, pigmentation of iris, dark coloration, striated constrictions of abdominal wall, poor appetite, anemia, poor growth
Pyridoxine-B6	Hyper-irritability, nervous disorders, anemia, rapid rigor mortis, loss of appetite, peritoneal edema cavity, rapid breathing, colorless serous fluid, exophthalmia
Pantothenic acid-B5 or Acetyl coenzyme A	Necrosis, clubbed gills, cellular atrophy of gills, gill exudate, lethargy, loss of appetite, poor growth, skin hemorrhage, skin lesions, and deformities
Niacin	Anorexia, poor growth, lethargy, and mortality
Inositol	Distended stomach, increased gastric emptying time, depigmentation, skin lesions, and poor growth
Biotin-B7	Loss of appetite, altered coloration, lesions in colon, skin lesion, muscle atrophy, spastic convulsions and fragmentation of erythrocytes, and poor growth
Folic acid-B9	Macrocytic anemia, lethargy, fragility of caudal fin, dark coloration, poor growth
Choline	Poor food conversion, poor growth, hemorrhagic kidney and intestine, accumulation of neutral fat in hepatopancreas, enlarged liver
Nicotinic acid	Loss of appetite, poor growth, jerky motion, lesions in colon, weakness, edema, muscle spasms while resting, sensitivity to sunlight, skin hemorrhage, lethargy, and anemia
Vitamin B	Poor appetite, low hemoglobin, fragmentation of erythrocytes, macrocytic anemia, reduced growth
Vitamin C	Impaired collagen formation, hemorrhagic skin, liver, kidney, and muscle, eye lesions, anorexia, reduced growth, dark coloration, fin necrosis, loss of balance, high mortality
Vitamin A	Ascites, ceroid in liver, spleen, and kidney, anemia, the fragility of red blood cells, exophthalmia, poor growth, depigmentation, kidney hemorrhages, and soft exoskeleton
Vitamin D	Poor feed utilization, slow growth rate, raised blood counts, poor growth, decreased ash levels, calcium, and phosphorus, soft exoskeleton, lethargy
Vitamin E	Muscular dystrophy, pathological condition in reproductive organs, increased permeability of capillaries, hemorrhages and edema in various parts of the body
Vitamin K	Anemia, prolonged coagulation time

Table 4 Different minerals and their body function, deficiency signs in fishes (Shefat and Karim 2018)

Mineral	Body function	Deficiency symptoms
Calcium and phosphorus	Bone formation, supply high energy phosphorus compounds, blood clotting	Lordosis, scoliosis, slow growth rate and increased mortalities, and skull deformities
Magnesium	Act as enzyme cofactor, involved in intra- and extracellular homeostasis and in cellular respiration	Poor growth, lordosis and protein growth, tetany
Iron	Essential constituent of heme, cytochromes, and peroxidases	Microcytic homochronic anemia
Manganese	Bone formation, involved in erythrocyte regeneration and arginase cofactor	Loss of equilibrium, sluggish movement, poor appetite, weight loss, and mortality
Iodine	Regulate total oxygen usage	Thyroid, hyperplasia (goiter)
Potassium	Maintains osmoregulation, intracellular ionic balance muscular contraction neurotransmission	Reduced feed efficiency and growth, anorexia, tetany, convulsion, death
Zinc	The activity of dehydrogenases, peptidases, aldolases, dismutase, and phosphates involved in digestion is Zn dependent, protection against autoxidation	Loss of appetite, reduced growth, cataracts, high mortality, erosion of fins and skin, elevated tissue concentration of Fe and Cu in intestine, short body dwarfism, and fin erosion
Copper	Facilitates absorption of Fe and Zn, involved in electron transport; cytochrome oxidase, SOD, catalase, tyrosinase are Cu dependent enzymes	Reduced growth and cataract
Selenium	Prevention of lipid autoxidation, as SOD cofactor, required for the functioning of glutathione peroxidase	Increased mortality, muscular dystrophy, depressed glutathione peroxidase activity, reduced growth

However, it is known that phosphorus is the most critical macromineral in fish diets because of its minimal occurrence in culture water.

Phosphorus constitutes hard tissues like scales and bones and is further available as a biochemical component. Impaired growth, reduced tissue mineralization, feed efficiency, and impaired skeletal formation in juvenile fish are common symptoms when fish are fed on a phosphorus-deficient diet (Imelda and Paulraj 2002). Macrominerals like chloride, sodium, and potassium are other key elements that help to regulate osmoregulation and acid-base maintenance in fishes (Imelda and Paulraj 2002). They are found abundantly in water as well as in practical fish diets.

Microminerals or trace minerals include iodine, cobalt, chromium, iron, copper, selenium, manganese, and zinc. Micro-mineral deficiencies (Table 4) do not readily impair growth and feed efficiency; however, a prolonged feeding of deficient diets can induce severe disturbances on growth and physiology (Imelda and Paulraj 2002). Copper, iron, manganese, selenium, and zinc represent the most important mineral supplement in diets since practical feed ingredients contain low levels of these microminerals, and furthermore their interactions with other dietary components may reduce their bio-availability for the fishes. To overcome this, an inexpensive trace mineral premix can be added to the diets in order to meet the adequate requirement of trace minerals in fish diets. Minerals provide important roles in scale and skeleton formation, osmoregulation, and intermediary metabolism in fish. Some of the other minerals are absorbed from water in significant quantities via gills as well as from the diet. Mostly mineral deficiencies appear either due to dietary imbalances or by the interaction of different dietary components. Skeletal deformities, reduced resistance to diseases and anemia are some mineral deficiency signs (Imelda and Paulraj 2002; Joseph and Raj 2002). Micronutrients such as zinc, copper, iron, and selenium serves as metallo-enzymes which are vital for maintaining cellular functions in the immune system. On the other hand, very little information is available about the effects of trace elements on the immune function of finfish species.

10 Options for Climate Change Adaptations in Aquaculture Through Functional Foods

The prime goal in any type of aquaculture system is to maximize production efficiency to optimize profitability. The concept of functional aquafeeds can be considered as an emerging new paradigm for developing diets for fishes and crustaceans. The importance of functional feeds extends beyond fulfilling basic nutritional requirements in fishes, it not only accounts for improved growth and feed utilization, but also elevate and support general health and stress resistance of the animals. Functional feeds are considered to promote the growth and health of cultured organisms, improve their immune system, and induce physiological benefits beyond the scope of conventional feeds. It must also be economically feasible and environmental friendly. In this context, the inclusion of animal products as well as byproducts in functional feed formulations should be partially or totally excluded and increasing the inclusion of alternative economical green products can be done. However, the quantity and quality of vegetable protein, carbohydrates (CHO), and lipids added to formulations are of major concern for growth and health of the fishes, further its effect on environment and economic should be analyzed. Functional aquafeeds can also improve feed conversion, decrease nutrient leaching from the feed, and fine-tune target species excretion, thus minimizing nutrient loadings on aquatic ecosystems.

11 Functional Feeds Used in Aquaculture

As we understand that the acceleration of the aquaculture sector is obstructed by the changing face of the climatic regime, adequate action needs to be taken to tackle the obstacle through dietary approaches. In this midst, nutritional biotechnology offers a suitable platform to overcome the different environmental and human-intended stressors to sustain fishes' optimal growth and health status under culture. In this aspect, there is a plethora of published literature on the application of functional

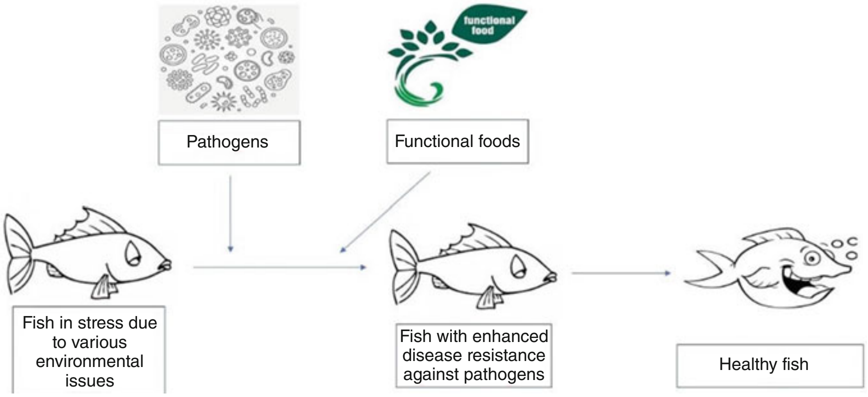

Fig. 2 Role of functional foods to mitigate the adverse effects of climate change by modulating the immune system and enhancing disease resistance in fish

foods to augment the production of fish. When added to feeds, there are some specific ingredients that affect the physiology and metabolism of the target animal. These feed supplements in diets provide health benefits, apart from supplementing the basic nutrient requirements of the organism. Thus, in short, functional foods are ingredients/additives that can offer health benefits that extend beyond their nutritional value. In the modern aquafeed industries, a wide variety of additives are being extensively used to supplement the primary nutrients essential for a particular fish. However, along with the ingredients supplying energy and essential nutrients, there is a need to incorporate such additives that impart some extra functionality to the feed, e.g., reducing the adverse effects of anti-nutritional factors, immunity-boosting, providing resistance against a wide variety or a particular disease (s), etc. (Ringo et al. 2012). With the increase in intensification of aquaculture, the chances of disease outbreak due to various types of stressors have enormously accelerated. Thus, the management practices aiming at the immune-competence of fish stocks have focused on the last few decades. The use of functional ingredients in feeds has synergically increased with the intensification of fish culture and has shown remarkable results in increased growth performance, immune responses, and disease resistance.

These selective additives (functional ingredients) may be in the form of natural ingredients, nutraceuticals, essential nutrients, etc. and are meant to increase the health status, reduce infection, and increase the immunity of fish against environmental stresses (Waagbø 2006). Some of the commonly used functional feed additives in aquaculture include prebiotics, probiotics, immune-stimulants, enzymes, antioxidants, vitamins, plant extracts, and organic acids (Nakagawa et al. 2007). Functional feeds provide an easy and natural way to mitigate the adverse effects of infectious diseases and other stress-related problems. A simple depiction of the role of functional foods in modulating the immune system to enhance disease resistance in fish is given in Fig. 2. The modes of action of these functional additives are multidimensional and need to be understood to provide a viable means for supporting the health status of the fish under climate severity.

11.1 Prebiotics

After decades of research on probiotic application in aquatic animals, scientist across the globe has started parallel application of related entity known as prebiotics. The successful incorporation of prebiotic in human and animal diet has opened the door for its application and trial in fishes too. As described by Gibson and Roberfroid (1995), prebiotics are the "non-digestible food ingredients that impart benefit to the host by selectively stimulating the growth and/or activity of single or a limited number of bacteria in the colon," purposively serving as direct food for the probiotic microbes. Prebiotics generally consist of dietary fiber complex of carbohydrates that are resistant to gastric (acidic) digestion and can act as a substrate for the growth and propagation of good probiotic bacteria colonizing the gut of the host. Oligosaccharides of 3–10 monosaccharide units act specifically as prebiotics (Gibson and Roberfroid 1995), and the most commonly used oligosaccharides in the aqua industry include the mannan-oligosaccharides (MOS) and fructo-oligosaccharides (FOS) with a lesser contribution from xylo-oligosaccharides (XOS) and galacto-oligosaccharide (GOS). Some non-starch polysaccharides (NSPs), other than non-digestible oligosaccharides, act as prebiotics, and this category includes glucans and inulin. β-glucans are the polysaccharide of β-ᴅ-glucose and are mainly present in yeast cell walls. The most common commercial prebiotics in aquaculture is derived from yeast extracts, barley/yeast-derived beta-glucan, and MOS products. A number of studies have revealed that the inclusion of MOS in aquafeeds helps to increase the growth performance of Atlantic salmon, gilthead seabream, European sea bass, Nile tilapia, rainbow trout, and white-leg shrimp (Table 5). Also, the current scenario of prebiotics reveals that MOS and β-glucans are the most frequently used prebiotics in intensive aquaculture systems, followed by yeast extract, inulin, etc.

Mode of Action of Prebiotics

There are many theories available in the literature describing the mode of action of different prebiotics. For example, Torrecillas et al. (2014) reported that MOS triggers stimulation of feed intake as well as digestibility of nutrients, thus increasing the growth performance and improvement in gut interiority. The activity of enterocytes leading to enhanced absorption and nutrient transport has been observed when supplemented with β-glucans and MOS (Dimitroglou et al. 2011). In some cases, prebiotics may only help to boost immunity and thus disease resistance (Bagni et al. 2005; Luna-González et al. 2012). This disease resistance may also be attributed to the proliferation of beneficial bacteria competing with pathogenic microorganisms of the gut (Torrecillas et al. 2014). The most commonly used prebiotics to enhance immune response includes β-glucans and MOS, which have been shown to increase the serum lysozyme activity, bactericidal activity, oxidative burst activity, nitric oxide, leukocyte phagocytic activity in European sea bass, rainbow trout, and many other commercially important fish species (Table 5). Other possible functionality of prebiotics includes stimulation of gut-associated lymphoid tissue (GALT) and reduced bacterial translocation in the gut (Torrecillas et al. 2007, 2011). In many

Table 5 Prebiotics and their effects on common aquaculture species

Species	Prebiotic	Dose	Effects	References
European sea bass	Beta-glucan	1 g/kg	Increased immunity ↔ growth, ↔ FCR, increased	Bagni et al. (2005)
Nile tilapia	Beta-glucan and yeast extract	10 g/kg glucans or yeast extract	Increased immunity as well as disease resistance	El-Boshy et al. (2010)
Salmon	Beta-glucans and MOS Atlantic	0.5–1 g/kg glucans or 1–2 g/kg MOS	Increased growth (only MOS), increased disease resistance (only glucans)	Refstie et al. (2010)
Atlantic salmon	FOS and MOS	10 g/kg FOS or MOS	↔ Growth, increased E retention, increased immunity (only MOS)	Grisdale-Helland et al. (2008)
White-leg shrimp	FOS	0.25–8.0 g/kg	Increased immunity, ⍰ gut bacterial composition	Li et al. (2007)
Atlantic salmon	Inulin	75 g/kg	Decreased bacterial counts, decreased gut bacterial diversity	Bakke-McKellep et al. (2007)
White-leg shrimp	Inulin	1.25–10 g/kg	↔ Growth, increased immunity, increased disease resistance	Luna-González et al. (2012)
Rainbow trout	Inulin and FOS	5–10 g/kg inulin or FOS	Increased growth, ⍰ gut bacterial composition (only inulin)	Ortiz et al. (2013)
Atlantic salmon	MOS 4 g/kg	4 g/kg	↔ Growth, increased N retention, increased disease resistance	Dimitroglou et al. (2011)
Gilthead seabream	MOS	2 or 4 g/kg	Increased growth, increased N and C digestibility	Gültepe et al. (2011)
Rainbow trout	MOS	2.5 or 5 g/kg	Increased growth, reduced decreased FCR, increased N retention, increased immunity, increased disease resistance	Rodriguez-Estrada et al. (2013)
European sea bass	MOS	0.2 or 0.4 g/kg	Increased immunity, increased disease resistance	Torrecillas et al. (2007)
European sea bass	MOS	2, 4 or 6 g/kg	↔ Growth, decreased FCR, increased immunity	Torrecillas et al. (2011)
Rainbow trout	MOS and yeast	6 g/kg MOS or 5 g/kg yeast	⍰ Bacterial composition, increased gut bacterial diversity (NGS)	Gonçalves and Gallardo-Escárate (2017)
Rainbow trout	Yeast extract and MOS	10 g/kg extract or 4–10 g/kg MOS	↔ Growth, ↔ FCR, ⍰ gut bacterial composition (NGS)	Betiku et al. 2017
Rainbow trout	Yeast extract	5 g/kg yeast extract or powder	Increased immunity, increased disease resistance	Tukmachi and Bandboni (2014)

(Modified from Boyd et al. 2020)

N nitrogen (protein), *E* energy, *C* carbohydrate, *FCR* feed conversion ratio, *FOS* fructo-oligosaccharides, *MOS* mannan-oligosaccharides, *NGS* next-generation sequencing species like Atlantic salmon, European sea bass, Nile tilapia, and rainbow trout, the supplementation of beta-glucans and MOS has shown a significant decrease in their mortalities when challenged with pathogens such as *Aeromonas hydrophila*, sea lice, and *Vibrio* spp. (Rodriguez-Estrada et al. 2013).

The prominent microbiota present in farmed fish and shrimp gut constitutes the *Proteobacteria, Bacteroidetes, Firmicutes, Fusobacteria*, and *Actinobacteria* phyla (Cornejo-Granados et al. 2018). Next-generation sequencing (NGS) technology is used to identify gut microbes, and most of the studies have reported that prebiotics help reduce the proliferation of pathogenic bacteria such as *Aeromonas* and *Vibrio* spp. (Proteobacteria phylum), while increasing the beneficial lactic acid bacteria, such as *Lactobacillus* and *Enterococcus* (Firmicutes phylum). Considering this scenario, the wise application of prebiotics with a focus on the population proliferation of the desired micro-flora in the fish gut needs to be considered.

11.2 Probiotics

According to Fuller (1989), probiotics are living microbes administered orally to an animal and can colonize the gut to exert multiple benefits to the host. Some of the most commonly used probiotics in aquaculture include bacteria species of Lactobacillus, Bacillus, Lactococcus, Enterococcus, and Pediococcus, as well as brewer's yeast *Saccharomyces cerevisiae* (Table 6). Most frequently, probiotics are gram-positive bacteria that participate in the development of the gut, provide mucosal tolerance, increase immune response and disease resistance (Ringo et al. 2018). Conversely, the gut microbiota also includes the yeasts, which produce phytases helpful in producing antimicrobial peptides to inhibit the growth and proliferation of pathogenic microorganisms (Navarrete and Tovar-Ramírez 2014). Since probiotics are sensitive to high temperatures, they are added to the feed either after proper cooling of the cooked feed mixture and then cold-pressed to make the pellets or directly sprayed on the feed pellets to avoid temperature or pressure shock.

Many studies have validated the efficiency of probiotics in enhancing the growth performance and feed utilization of commercially important fish species like Nile tilapia, Rainbow trout, and several other aquaculture species (Table 6).

Mode of Action of Probiotics

Probiotics help to boost growth performance and feed utilization mainly via increasing the efficiency of metabolic pathways through different activities; they may contribute some vitamins such as vitamin K and B_{12}, they may produce digestive enzymes that are normally not produced by the host and may also supply some short-chain fatty acids to the host (Merrifield et al. 2010). Yeast probiotics may also help in the rapid development of the digestive system in young rainbow trout fry via enhanced alkaline phosphatase and leucine-aminopeptidase activity (Waché et al. 2006). Finally, probiotics are reported to modulate the immune system and enhance disease resistance which is very crucial considering the problems of increasing antimicrobial resistance. According to Nayak (2010), probiotics interact with

Table 6 Probiotics and their effects on common aquaculture species

Species	Probiotic	Dose	Effects	References
Oreochromis niloticus, Nile tilapia	*Bacillus amyloliquefaciens*	10^4 or 10^6 CFU/g	Increased immunity, increased resistance to disease	Selim and Reda (2015)
Oreochromis niloticus, Nile tilapia	*B. amyloliquefaciens* or *lactobacillus* spp.	10^8 CFU/g	Increased growth, ↔ FCR, increased immune system, increased gut microbiome	Raida et al. (2003)
Litopenaeus vannamei, White-leg shrimp	*B. coagulans*	10^6, 10^7, or 10^8 CFU/g	Increased growth, decreased FCR, increased immunity, increased disease resistance, increased gut bacterial flora, □ gut bacterial composition (NGS)	Amoah et al. (2019)
Litopenaeus vannamei, White-leg shrimp	*B. licheniformis*	10^4 CFU/g	Increased growth, increased immunity, increased water quality, increased survival	Franco et al. (2017)
Sparus aurata, gilthead seabream	*B. subtilis*	10^7 CFU/g	Decreased gut bacteria diversity, □ gut bacteria composition	Cerezuela et al. (2013)
Oncorhynchus mykiss, rainbow trout	*B. subtilis*	10^7 CFU/g	Increased immunity, increased disease resistance, decreased bacterial counts	Newaj-Fyzul et al. (2007)
Oncorhynchus mykiss, rainbow trout	*B. subtilis* and *B. licheniformis*	10^8, 10^9, or 10^{10} CFU/g	Increased growth, decreased FCR, increased N retention, increased gut bacterial counts, increased survival, □ gut bacterial composition	Bagheri et al. (2008)
Oreochromis niloticus, Nile tilapia	*Enterococcus faecium*	10^7 CFU/g	Increased growth, increased immunity	Wang et al. (2008)
Oncorhynchus mykiss, rainbow trout	*E. casseliflavus*	10^7, 10^8, or 10^9 CFU/g	Increased growth, decreased FCR, increased immunity, increased gut bacterial counts, increased disease resistance	Safari et al. (2016)
	E. faecalis	2.5 or 5 g/kg	Increased growth, decreased FCR,	Rodriguez-Estrada

(continued)

Table 6 (continued)

Species	Probiotic	Dose	Effects	References
Oncorhynchus mykiss, rainbow trout			increased N retention, increased immunity, increased disease resistance	et al. (2013)
Oreochromis niloticus, Nile tilapia	*Lactobacillus acidophilus*	10^7 CFU/g	Increased immunity, increased disease resistance	Villamil et al. (2014)
Oreochromis niloticus, Nile tilapia	*L. plantarum*	0.05–0.2 g/kg	Increased growth, decreased FCR, increased N retention, increased immunity, increased disease resistance	Hamdan et al. (2016)
Oncorhynchus mykiss, rainbow trout	*L. rhamnosus*	10^9, 10^{10}, or 10^{11} CFU/g	Increased immunity, increased gut bacterial counts	Panigrahi et al. (2004)
Oncorhynchus mykiss, rainbow trout	*L. rhamnosus*	10^{11} CFU/g (heat-killed, spray-dried or freeze-dried)	Increased immunity (only SD and FD), decreased gut bacterial counts (only SD and FD)	Panigrahi et al. (2005)
Oreochromis niloticus, Nile tilapia	*L. rhamnosus*	10^{10} CFU/g	Increased immunity, increased disease resistance	Pirarat et al. (2006)
Litopenaeus vannamei, Whiteleg shrimp	*L. lactis*	10^6, 10^7, or 10^8 CFU/g	Increased growth, decreased FCR, increased N retention, increased gut bacterial counts, increased survival, increased disease resistance	Adel et al. (2017)
Litopenaeus vannamei, White-leg shrimp	Mix of *B. subtilis, B. licheniformis*, and *lactobacillus* sp.	1–8 g/kg	Increased growth, decreased FCR, increased immunity, increased gut bacterial diversity, ⍰ gut bacterial composition (NGS)	Xie et al. (2019)
Oreochromis niloticus, Nile tilapia	Mix of *B. subtilis, E. faecium, L. reuteri*, and *Pediococcus acidilactici*	1.5 or 3 g/kg	Increased growth, ↔ FCR, increased immunity, increased gut bacterial counts, ⍰ gut bacterial composition	Standen et al. (2016)
Oreochromis niloticus, Nile tilapia	Mix of *B. subtilis, L. acidophilus, Clostridium butyricum*, and yeast	10 g/kg	Increased immunity, increased disease resistance	Taoka et al. (2006)

(continued)

Table 6 (continued)

Species	Probiotic	Dose	Effects	References
Salmo salar, Atlantic salmon	*P. acidilactici*	3.5 or 7 g/kg	↔ Growth, ↔ FCR, increased immunity, increased gut bacterial diversity, decreased gut bacterial counts	Abid et al. (2013)
Onchorhynchus mykiss, rainbow trout	*P. acidilactici*	10^6 CFU/g	↔ Growth, increased immunity, ⍰ gut bacteria composition, ↔ gut bacterial diversity (NGS)	Ingerslev et al. (2014)
Oreochromis niloticus, Nile tilapia	*P. acidilactici*	10^6 CFU/g	↔ Growth, ↔ FCR, increased immunity	Standen et al. (2013)
Onchorhynchus mykiss, rainbow trout	*P. acidilactici* or yeast	10^6 CFU/g	↔ Growth, increased disease resistance, decreased gut bacterial counts (only PA)	Aubin et al. (2005)
Oreochromis niloticus, Nile tilapia	Yeast	0.5–5 g/kg	Increased growth, decreased FCR, increased N and E retention, increased immunity, increased disease resistance	Abdel-Tawwab et al. (2008)
Onchorhynchus mykiss, rainbow trout	Yeast	5 g/kg	Increased gut bacterial diversity, ⍰ gut bacterial composition (NGS)	Gonçalves and Gallardo-Escárate 2017
Onchorhynchus mykiss, rainbow trout	Yeast	214 g/kg	↔ Bacterial counts, increased bacterial diversity, ⍰ bacteria composition (NGS)	Huyben et al. (2018)
Oreochromis niloticus, Nile tilapia	Yeast	10^7 CFU/g (live and inactivated)	Increased Growth (only live), ↔ FCR, increased immunity, increased disease resistance, ⍰ gut bacterial composition (NGS)	Ran et al. (2015)
Onchorhynchus mykiss, Rainbow trout	Yeast	10 g/kg	Increased digestive enzymes, increased immunity, ⍰ gut bacterial composition	Waché et al. (2006)

(Modified from Boyd et al. 2020)
CFU colony-forming unit, *FD* freeze-dried, *N* nitrogen (protein), *E* energy, *FCR* feed conversion ratio, *NGS* next-generation sequencing, *SD* spray-dried

phagocytic cells, neutrophils, and natural killer cells to activate the innate immunity of fish. The immune responses due to supplementation of several probiotics include increased levels of bactericidal, lysozyme, respiratory burst, peroxidase, leucocyte counts, and/or complement activities and gene expression of inflammatory cytokines. The property of probiotics to boost innate immunity imparts more chances of survival when exposed to different fish pathogens of various species of *Aeromonas, Streptococcus,* and *Yersinia*. Apart from fishes, the probiotics are also equally effective in shrimps and primarily provide disease resistance against white spot syndrome virus (WSSV) in white-leg shrimp (Zuo et al. 2019).

11.3 Synbiotic Application in Aquafeeds

The popularity of both probiotic and prebiotic applications in aquafeed as a separate entity is well established. When applied in singular mode, the unique functionality of these biotic components has attracted researchers across the countries to try their combined application to exert a profound effect that may exaggerate a better level of benefits to cultured aquatic animals. The general understanding is that any two biotic components applied in biological science may benefit the host organisms from three possible angles, viz. addition, synergism, or potentiation. In the case of synbiotics, the interaction known as synergism works for enhanced activity of the paired components, compared to their individual use. As per the most accepted definition provided by Gibson and Roberfroid (1995), synbiotic refers to "a mixture of probiotics and prebiotics that beneficially affects the host by improving the survival and implantation of live microbial dietary supplements in the gastrointestinal tract, by selectively stimulating the growth and/or by activating the metabolism of one or a limited number of health-promoting bacteria and thus improving host welfare." Therefore, in a synbiotic formula, the synergistic effect of the used micro-organism depends on its ability to improve host immunity, whereas the prebiotic potentiates towards stimulating growth and activity of the used micro-organism known as the micro-organism probiotic. It is to be noted that any combination of pro- and prebiotic does not necessarily form a synbiotic formula, as the resulting effect may vary depending upon the action that is mentioned above. A wide range of research on synbiotic formulation using both probiotic and prebiotic is reported and presented in Table 7.

12 Nutri-Enzyme in Aquafeed

The application of exogenous enzymes for enhancing feed efficiency is a lucrative concept well explored in farmed terrestrial animals and is being adapted for aquaculture species. The main purpose of nutri-enzyme supplementation in aquafeeds is to improve digestion of the supplied feed. It is established that these extra doses of enzymes improved the digestive processes to stimulate better results in terms of improved feed efficiency. The extended role of these nutri-enzymes also comes in

Table 7 Recent studies on the synbiotic application in fishes

Target species (g)	Probiotic	Prebiotic	Benefits	References
Oncorhynchus mykiss	*Enterococcus faecalis* (1%)	MOS (0.4%)	Increased immune function and disease resistance	
Larimichthys crocea	*B. subtilis* (0.42 × 10^7 and 1.35 × 10^7 CFU/g)	FOS (0, 2, and 4 g/kg)	Increase SGR and FER; disease resistance	
Rachycentron canadum	*B. subtilis* (0.1 × 10^{10} and 2 × 10^{10} CFU/g)	Chitosan (3 and 6.0 g/kg)	Increased growth, immunity, and disease resistance	
Paralichthys olivaceus	*B. clausii* (10^7 CFU/g)	FOS + MOS (2.5 g + 2.5 g/kg)	Increased weight gain Elevated digestive enzyme activity Increased immune system	
		MOS (5 g/kg)	Increased gut protease activity Increased growth, health benefits	
Oncorhynchus mykiss	Biomin IMBO, (*enterococcus faecium*, 5 × 10^{11} CFU/kg) + FOS) (0, 0.5, 1, and 1.5 g/kg)		Increased growth and feed efficiency	
Pseudoplatystoma sp.	*Weissella cibaria* (CPQBA 001-10 DRM 02) (7.87 ± 0.2 log CFU/g)	Inulin (0.5%)	Increased gut microbiota and haemato-immunology	
Labeo fimbriatus	*B. subtilis* (10^4 CFU/g)	MOS (5 g/kg)	Increased growth performance and feed efficiency	
Sparus aurata	*B. subtilis* (10^7 CFU/g)	Inulin (10 g/kg)	Decreased bacterial diversity	Cerezuela et al. (2013)
Trachinotus ovatus	*Bacillus subtilis* (5.62 × 10^7 CFU/g)	FOS (0.2%/kg)	Increased growth, increased immunity and disease resistance	
Megalobrama terminalis	*Bacillus licheniformis* (10^7 CFU/g)	FOS (3 g/kg)	Increased growth performance, intestinal Enzymes activity	
Husohuso	Biomin IMBO (Biomin, Herzogenburg, Austria) (*Enterococcus faecium* 5 × 10^{11} CFU/kg + FOS)		Increased innate immunity	

(continued)

Table 7 (continued)

Target species (g)	Probiotic	Prebiotic	Benefits	References
Salmo trutta caspius	BetaPlus® @ 1 g/kg diet (BioChem Co., Karlsruhe, Germany) containing *B. subtilis* + *B. licheniformis* (5.12 × 10^{12} (CFU)/kg for each strain ^{1})	Isomalto oligosaccharides (IMOS) (2 g/kg)	Increased growth, immune parameters	
Cirrhinus mrigala	*Bacillus subtilis* (15% × 10^{7} CFU/mL)	(MOS) 0.6%/kg	Increased innate immunity and disease resistance	
Anguilla japonica:	*Bacillus subtilis WB60* (0.5 × 10^{7} CFU/g)	(MOS) 5 g/kg	Increased growth performance, non-specific immune responses, intestinal morphology and disease resistance	
Catla catla	*Bacillus subtilis ATCC 6633* (10^{6} CFU/g)	(MOS) 0.4%	Increased growth	
Oreochromis niloticus	Synbiotic (0.7 or 1.5 g/kg) (Lacto Forte: β-glucan 30 g, MOS 30 g, *Enterococcus faecium* 6 × 10^{12} CFU, *Bacillus subtilis* 6 × 10^{12} CFU, and dextrose to 1 kg)		No influence on growth and immune response; long-term feeding at high dose, i.e., 1.5 g/kg exerts negative health impact	
Anguilla japonica	*Bacillus subtilis* KCTC 2217/*Bacillus licheniformis* KCCM 11,775 (10^{8} CFU/g)	MOS or FOS (5 g/kg)	Increased weight gain and disease resistance	
Labeo rohita	*Bacillus circulans PB7 (BCPB7)* (10^{6} CFU/g$^{)}$	FOS (10 g/kg)	Increased protection to low water pH	

position as some of the fishes lack certain digestive enzymes during the early life stages or may be throughout their life. Therefore, for fish larvae lacking some of the key enzymes in their body, exogenous provision enables the fishes to utilize the fed diets.

The earliest studies on the use of exogenous enzymes in cultured fishes were conducted with enzymes extracted from the gut of fishes. Since then, a series of work has been accomplished and presently, the application of exogenous enzymes is being followed for several aquaculture species. Among the many, these nutri-enzymes provide three basic functions, viz. reducing the negative effects of anti-nutritional factors (e.g., phytase), increasing the digestion of non-starch polysaccharides (e.g., xylanase, cellulase), and accelerating protein digestion (e.g., proteases) (Castillo and Gatlin 2015). However, most enzymes have been used to digest carbohydrates and increase the utilization of phytate phosphorus present in ingredients of plant sources. Several carbohydrase enzymes like xylanases, cellulases, α-galactosidases, and β-glucanases are used for different aquaculture species (Jacobsen et al. 2018b). Many times, enzyme supplementation shows mixed effects, e.g., the supplementation of α-galactosidase to rainbow trout feeds containing lupins showed increased energy and protein digestibility (Glencross et al. 2003). A dual property of phytases has been reported for alleviating the anti-nutritional property of phytate as well as elevating the phosphorus utilization from plant sources in many aquaculture species (Kumar et al. 2012). Apart from the phosphorus and protein digestibility, phytase supplementation also results in enhancing the availability of other minerals in various salmonid species (Sugiura et al. 2001).

However, it seems to be a general rule that the functions of exogenous enzymes, especially carbohydrases depend on the type of ingredients used for feed formulation and the species being cultured. For example, Dalsgaard et al. (2016) observed significant benefits from β-glucanase but limited benefits from xylanase in soybean-based diets; Jacobsen et al. (2018a, 2018b) reported no benefit when a range of enzymes like protease, phytase, xylanase, and cellulase was used in the diet of Atlantic salmon. Further, Maas et al. (2018) reported that supplementation of exogenous preparations of xylanase and β-glucanase in the diets of tilapia gave better results in comparison to salmonids. But in most cases, exogenous enzyme supplementation results in increased growth and feed conversion. While in some cases, it may lead to elevated nutrient digestibility of aquafeeds (Maas et al. 2018). Also, phytase supplemented Tilapia diets have clearly shown greater positive effects (Liebert and Portz 2007; Maas et al. 2018).

Conversely, protease supplementation in the soybean meal-based diets of Gibel carp and Nile tilapia has reported promising results in enhancing the growth performance, FCR, and digestibility (Shi et al., 2016). However, very little literature is available on the use of proteases in aquaculture, thus more elaborated studies are required in this area.

13 Conclusion

Over the century, the galloping human population increase demands more food production and aquaculture stands alone as a sector with a promising future. The alarming climate change-induced severity brings a critical stand-off between production enhancement and technology. Studies show that the climate change-induced consequences are going to be random across geographical locations across the globe. For that matter, it becomes imperative to understand the adoption and culture practice of the existing aquaculture systems in diverse latitudes in the tropical, sub-tropical, and temperate regions of the world in order to be able to build future scenarios of likely impacts of climate change on aquaculture. In comparison to other latitudes, the aquaculture activities in the tropical belt are likely to forecast serious mortalities and quicker spread of diseases, and this is likely to be aggravated by global climate change events that can lead to emergence of virulent and lethal pathogens that have the capability to spread geographically. Studies in relation to intricate interactions between aquatic animal disease and climate change in aquaculture systems need to be conducted for better management of these arising problems. Detailed study regarding interaction between climate-sensitive aquaculture and their aquatic hosts and climate-sensitive aquatic diseases, mapping potential risks, identification of suitable adaptation/mitigation, and prevention or intervention strategies should be the focal point of research and development in order to meet the future seafood demand for nine billion people by 2050. Amidst this alarming situation, the functionality and usefulness of dietary nutrients that can enhance the immune system and overall performance of fishes in culture need to be identified and applied wisely. The functional foods described in this chapter represent some of the most important plethora available. Their effectiveness in various species models is predictable depending on the laboratory scale trial and needs evaluation on a field basis to have a tangible overall outcome.

References

Abdel-Tawwab M, Abdel-Rahman AM, Ismael NEM (2008) Evaluation of commercial live bakers' yeast, Saccharomyces cerevisiae as a growth and immunity promoter for Fry Nile tilapia, Oreochromis niloticus (L.) challenged in situ with Aeromonas hydrophila. Aquaculture 280: 185–189

Abid A, Davies SJ, Waines P, Emery M, Castex M, Gioacchini G, Merrifield DL (2013) Dietary synbiotic application modulates Atlantic salmon (Salmo salar) intestinal microbial communities and intestinal immunity. Fish Shellfish Immunol 35:1948–1956

Adel M, El-Sayed AM, Yeganeh S, Dadar M, Giri SS (2017) Effect of potential probiotic *Lactococcus lactis subsp. lactis* on growth performance, intestinal microbiota, digestive enzyme activities, and disease resistance of *Litopenaeus vannamei*. Probiotics Antimicrob Proteins 9(2): 150–156

Amoah K, Huang QC, Tan BP, Zhang S, Chi SY, Yang QH, Dong XH (2019) Dietary supplementation of probiotic Bacillus coagulans ATCC 7050, improves the growth performance, intestinal morphology, microflora, immune response, and disease confrontation of Pacific white shrimp, *Litopenaeus vannamei*. Fish Shellfish Immunol 87:796–808

Aubin J, Gatesoupe F-J, Labbe L, Lebrun L (2005) Trial of probiotics to prevent the vertebral column compression syndrome in rainbow trout (*Oncorhynchus mykiss Walbaum*). Aquacult Res 36:758–767

Bagheri T, Hedayati SA, Yavari V, Alizade M, Farzanfar A (2008) Growth, survival and gut microbial load of rainbow trout (*Onchorhynchus mykiss*) fry given diet supplemented with probiotic during the two months of first feeding. Turk J Fish Aquat Sci 8:43–48

Bagni M, Romano N, Finoia MG, Abelli L, Scapigliati G, Tiscar PG, Marino G (2005) Short- and long-term effects of a dietary yeast beta-glucan (Macrogard) and alginic acid (Ergosan) preparation on immune response in sea bass (*Dicentrarchus labrax*). Fish Shellfish Immunol 18:311–325

Bakke-McKellep AM, Penn MH, Salas PM, Refstie S, Sperstad S, Landsverk T, Krogdahl A (2007) Effects of dietary soyabean meal, inulin and oxytetracycline on intestinal microbiota and epithelial cell stress, apoptosis and proliferation in the teleost Atlantic salmon (*Salmo salar* L.). Br J Nutr 97:699–713

Betiku OC, Yeoman CJ, Gibson Gaylord T, Duff GC, Hamerly T, Bothner B, Sealey WM (2017) Differences in amino acid catabolism by gut microbes with/without prebiotics inclusion in GDDY-based diet affect feed utilization in rainbow trout. Aquaculture 490:108–119

Bowden TJ, Thompson KD, Morgan AL, Gratacap RM, Nikoskelainen S (2007) Seasonal variation and the immune response: a fish perspective. Fish Shellfish Immunol 22(6):695–706

Boyd CE, D'Abramo LR, Glencross BD, Huyben DC, Juarez LM, Lockwood GS, Valenti WC (2020) Achieving sustainable aquaculture: historical and current perspectives and future needs and challenges. J World Aquacult Soc 51(3):578–633

Brander KM (2007) Global fish production and climate change. Proc Natl Acad Sci 104(50): 19709–19714

Callaway R, Shinn AP, Grenfell SE, Bron JE, Burnell G, Cook EJ, Crumlish M, Culloty S, Davidson K, Ellis RP, Flynn KJ (2012) Review of climate change impacts on marine aquaculture in the UK and Ireland. Aquat Conserv Mar Freshwat Ecosyst 22(3):389–421

Castillo S, Gatlin DM III (2015) Dietary supplementation of exogenous carbohydrase enzymes in fish nutrition: a review. Aquaculture 435:286–292

Cerezuela R, Fumanal M, Tapia-Paniagua ST, Meseguer J, Moriñigo MA, Esteban MA (2013) Changes in intestinal morphology and microbiota caused by dietary administration of inulin and *Bacillus subtilis* in gilthead sea bream (*Sparus aurata* L.) specimens. Fish Shellfish Immunol 34:1063–1070

Cornejo-Granados F, Gallardo-Becerra L, Leonardo-Reza M, Ochoa-Romo JP, Ochoa-Leyva A (2018) A meta-analysis reveals the environmental and host factors shaping the structure and function of the shrimp microbiota. PeerJ 6:e5382

D'Abramo L, Slater MJ (2019) Climate change: response and role of global aquaculture. J World Aquacult Soc 51(4):710–714

Dalsgaard J, Bach Knudsen KE, Verlhac V, Ekmann KS, Pedersen PB (2016) Supplementing enzymes to extruded, soybean-based diet improves breakdown of non-starch polysaccharides in rainbow trout (*Oncorhynchus mykiss*). Aquacult Nutr 22(2):419–426

Dimitroglou A, Reynolds P, Ravnoy B, Johnsen F, Sweetman F, Johansen W, Davies SJ (2011) The effect of mannan oligosaccharide supplementation on Atlantic salmon smolts (*Salmo salar* L.) fed diets with high levels of plant proteins. J Aquacult Res Dev S1:011. https://doi.org/10.4172/2155-9546.S1-011

El-Boshy ME, El-Ashram AM, Abdelhamid FM, Gadalla HA (2010) Immunomodulatory effect of dietary Saccharomyces cerevisiae, beta-glucan and laminaran in mercuric chloride treated Nile tilapia (*Oreochromis niloticus*) and experimentally infected with *Aeromonas hydrophila*. Fish Shellfish Immunol 28:802–808

Franco R, Martín L, Arenal A, Santiesteban D, Sotolongo J, Cabrera H, Castillo NM (2017) Evaluation of two probiotics used during farm production of white shrimp *Litopenaeus vannamei* (Crustacea: Decapoda). Aquacult Res 48:1936–1950

Fuller R (1989) Probiotics in man and animals. J Appl Bacteriol 66:365–378

Gibson GR, Roberfroid MB (1995) Dietary modulation of the human colonic microbiota: introducing the concept of prebiotics. J Nutr 125:1401–1412

Glencross BD, Boujard T, Kaushik SJ (2003) Influence of oligosaccharides on the digestibility of lupin meals when fed to rainbow trout, Oncorhynchus mykiss. Aquaculture 219(1–4):703–713

Gonçalves A, Gallardo-Escárate C (2017) Microbiome dynamic modulation through functional diets based on pre- and probiotics (mannan-oligosaccharides and *Saccharomyces cerevisia*e) in juvenile rainbow trout (*Oncorhynchus mykiss*). J Appl Microbiol 122:1333–1347

Grisdale-Helland B, Helland SJ, Gatlin DM (2008) The effects of dietary supplementation with mannanoligosaccharide, fructooligosaccharide or galactooligosaccharide on the growth and feed utilization of Atlantic salmon (*Salmo salar*). Aquaculture 283:163–167

Gültepe N, Salnur S, Hoşsu B, Hisar OLCAY (2011) Dietary supplementation with Mannanoligosaccharides (MOS) from Bio-Mos enhances growth parameters and digestive capacity of gilthead sea bream (*Sparus aurata*). Aquac Nutr 17(5):482–487

Halver JE (2002) The vitamins. In: Fish nutrition. Academic Press, San Diego, California, pp 61–141

Hamdan AM, El-Sayed AF, Mahmoud MM (2016) Effects of a novel marine probiotic, *Lactobacillus plantarum* AH 78, on growth performance and immune response of Nile tilapia (*Oreochromis niloticus*). J Appl Microbiol 120:1061–1073

Harvell CD, Kim K, Burkholder JM, Colwell RR, Epstein PR, Grimes DJ et al (1999) Emerging marine diseases—climate links and anthropogenic factors. Science 285(5433):1505–1510

Huyben D, Sun L, Moccia R, Kiessling A, Dicksved J, Lundh T (2018) Dietary live yeast and increased water temperature influence the gut microbiota of rainbow trout. J Appl Microbiol 124(6):1377–1392

Imelda J, Paulraj R (2002) Nutritional deficiency diseases in fish-Winter school on recent advances in diagnosis and management of diseases in mariculture, 7th to 27th November 2002, Course Manual

Ingerslev HC, von GersdorffJørgensen L, Lenz Strube M, Larsen N, Dalsgaard I, Boye M, Madsen L (2014) The development of the gut microbiota in rainbow trout (*Oncorhynchus mykiss*) is affected by first feeding and diet type. Aquaculture 424-425:24–34

Jacobsen HJ, Kousoulaki K, Sandberg AS, Carlsson NG, Ahlstrøm Ø, Oterhals Å (2018a) Enzyme pre-treatment of soybean meal: effects on non-starch carbohydrates, protein, phytic acid, and saponin biotransformation and digestibility in mink (Neovison vision). Anim Feed Sci Technol 236:1–13

Jacobsen HJ, Samuelsen TA, Girons A, Kousoulaki K (2018b) Different enzyme incorporation strategies in Atlantic salmon diet containing soybean meal: effects on feed quality, fish performance, nutrient digestibility and distal intestinal morphology. Aquaculture 491:302–309

Joseph J, Raj RP (2002) *Technical paper–8*. In: Nutritional deficiency diseases in fish, vol 682. Central Marine Fisheries Research Institute, Kochi, p 014

Ketola HG (1983) Requirement for dietary lysine and arginine by fry of rainbow trout. J Anim Sci 56(1):101–107

Kumar V, Sinha AK, Makkar HPS, De Boeck G, Becker K (2012) Phytate and phytase in fish nutrition. J Anim Physiol Anim Nutr 96(3):335–364

Li P, Burr GS, Gatlin DM III, Hume ME, Patnaik S, Castille FL, Lawrence AL (2007) Dietary supplementation of short-chain fructooligosaccharides influences gastrointestinal microbiota composition and immunity characteristics of Pacific white shrimp, *Litopenaeus vannamei,* cultured in a recirculating system. J Nutr 137(12):2763–2768

Liebert F, Portz L (2007) Different sources of microbial phytase in plant based low phosphorus diets for Nile tilapia *Oreochromis niloticus* may provide different effects on phytate degradation. Aquaculture 267(1–4):292–299

Luna-González A, Almaraz-Salas JC, Fierro-Coronado JA, Flores-Miranda MDC, González-Ocampo HA, PerazaGómez V (2012) The prebiotic inulin increases the phenoloxidase activity and reduces the prevalence of WSSV in whiteleg shrimp (*Litopenaeus vannamei*) cultured under laboratory conditions. Aquaculture 362-363:28–32

Maas RM, Verdegem MC, Dersjant-Li Y, Schrama JW (2018) The effect of phytase, xylanase and their combination on growth performance and nutrient utilization in Nile tilapia. Aquaculture 487:7–14

Mallick A, Panigrahi AK (2018) Effect of temperature variation on disease proliferation of common fishes in perspective of climate change. International Journal of Experimental Research and Review 16:40–49

Merrifield DL, Bradley G, Baker RTM, Davies SJ (2010) Probiotic applications for rainbow trout (*Oncorhynchus mykiss* Walbaum) II. Effects on growth performance, feed utilization, intestinal microbiota and related health criteria postantibiotic treatment. Aquacult Nutr 16:496–503

Mishra SS, Rakesh D, Dhiman M, Choudhary P, Debbarma J, Sahoo SN, Mishra CK (2017) Present status of fish disease management in freshwater aquaculture in India: state-of-the-art-review. J Aquac Fisheries 1:003. https://doi.org/10.24966/AAF-5523/100003

Nakagawa H, Sato M, Gatlin D III (eds) (2007) Dietary supplements for the health and quality of cultured fish. Cab International, Wallingford

Navarrete P, Tovar-Ramírez D (2014) Use of yeasts as probiotics in fish aquaculture. In: Hernandez-Vergara M (ed) Sustainable aquaculture techniques, pp 135–172

Nayak SK (2010) Probiotics and immunity: a fish perspective. Fish Shellfish Immunol 29:2–14

Newaj-Fyzul A, Adesiyun AA, Mutani A, Ramsubhag A, Brunt J, Austin B (2007) Bacillus subtilis AB1 controls Aeromonas infection in rainbow trout (*Oncorhynchus mykiss*, Walbaum). J Appl Microbiol 103:1699–1706

Ortiz LT, Rebolé A, Velasco S, Rodríguez ML, Treviño J, Tejedor JL, Alzueta C (2013) Effects of inulin and fructooligosaccharides on growth performance, body chemical composition and intestinal microbiota of farmed rainbow trout (*Oncorhynchus mykiss*). Aquacult Nutr 19:475–482

Panigrahi A, Kiron V, Kobayashi T, Puangkaew J, Satoh S, Sugita H (2004) Immune responses in rainbow trout Oncorhynchus mykiss induced by a potential probiotic bacteria *Lactobacillus rhamnosus* JCM 1136. Vet Immunol Immunopathol 102:379–388

Panigrahi A, Kiron V, Puangkaew J, Kobayashi T, Satoh S, Sugita H (2005) The viability of probiotic bacteria as a factor influencing the immune response in rainbow trout *Oncorhynchus mykiss*. Aquaculture 243:241–254

Pirarat N, Kobayashi T, Katagiri T, Maita M, Endo M (2006) Protective effects and mechanisms of a probiotic bacterium *Lactobacillus rhamnosus* against experimental *Edwardsiella tarda* infection in tilapia (*Oreochromis niloticus*). Vet Immunol Immunopathol 113:339–347

Poston HA, Riis RC, Rumsey GL, Ketola HG (1977) The effect of supplemental dietary amino acids, minerals, and vitamins on salmonids fed cataractogenic diets. Cornell Vet 67(4):472–509

Raida MK, Larsen JL, Nielsen ME, Buchmann K (2003) Enhanced resistance of rainbow trout, *Oncorhynchus mykiss* (Walbaum), against *Yersinia ruckeri* challenge following oral administration of *Bacillus subtilis* and *B. licheniformis* (BioPlus2B). J Fish Dis 26:495–498

Ran C, Huang L, Liu Z, Xu L, Yang Y, Tacon P, Zhou Z (2015) A comparison of the beneficial effects of live and heat-inactivated baker's yeast on Nile tilapia: suggestions on the role and function of the secretory metabolites released from the yeast. PLoS One 10:e0145448

Refstie S, Baeverfjord G, Seim RR, Elvebø O (2010) Effects of dietary yeast cell wall β-glucans and MOS on performance, gut health, and salmon lice resistance in Atlantic salmon (*Salmo salar*) fed sunflower and soybean meal. Aquaculture 305:109–116

Ringo E, Olsen RE, Vecino JG, Wadsworth S, Song SK (2012) Use of immunostimulants and nucleotides in aquaculture: a review. *J Mar Sci Res Dev* 2(1):104

Ringo E, Hossein S, Ghosh K, Doan HV, Beck BR, Song S (2018) Lactic acid bacteria in finfish—an update. Front Microbiol 9:1818

Rodriguez-Estrada U, Satoh S, Haga Y, Fushimi H, Sweetman J (2013) Effects of inactivated *Enterococcus faecalis* and mannan oligosaccharide and their combination on growth, immunity, and disease protection in rainbow trout. N Am J Aquac 75(3):416–428

Safari R, Adel M, Lazado CC, Caipang CM, Dadar M (2016) Host-derived probiotics *enterococcus casseliflavus* improves resistance against *streptococcus iniae* infection in rainbow trout (Oncorhynchus mykiss) via immunomodulation. Fish Shellfish Immunol 52:198–205

Selim KM, Reda RM (2015) Improvement of immunity and disease resistance in the Nile tilapia, *Oreochromis niloticus*, by dietary supplementation with *Bacillus amyloliquefaciens*. Fish Shellfish Immunol 44:496–503

Shi Z, Li XQ, Chowdhury MK, Chen JN, Leng XJ (2016) Effects of protease supplementation in low fish meal pelleted and extruded diets on growth, nutrient retention and digestibility of gibel carp, *Carassius auratus gibelio*. Aquaculture 460:37–44

Shefat SHT, Karim MA (2018) Nutritional diseases of fish in aquaculture and their management: a review. Acta Scientific Pharmaceutical Sciences 2(12):50–58

Standen BT, Rawling MD, Davies SJ, Castex M, Foey A, Gioacchini G, Merrifield DL (2013) Probiotic *Pediococcus acidilactici* modulates both localised intestinal- and peripheral-immunity in tilapia (*Oreochromis niloticus*). Fish Shellfish Immunol 35:1097–1104

Standen BT, Peggs DL, Rawling MD, Foey A, Davies SJ, Santos GA, Merrifield DL (2016) Dietary administration of a commercial mixed-species probiotic improves growth performance and modulates the intestinal immunity of tilapia, *Oreochromis niloticus*. Fish Shellfish Immunol 49:427–435

Sugiura SH, Gabaudan J, Dong FM, Hardy RW (2001) Dietary microbial phytase supplementation and the utilization of phosphorus, trace minerals and protein by rainbow trout [*Oncorhynchus mykiss* (Walbaum)] fed soybean meal based diets. Aquacult Res 32(7):583–592

Taoka Y, Maeda H, Jo JY, Kim SM, Park SI, Yoshikawa T, Sakata T (2006) Use of live and dead probiotic cells in tilapia *Oreochromis niloticus*. Fish Sci 72:755–766

Torrecillas S, Makol A, Caballero MJ, Montero D, Robaina L, Real F, Izquierdo MS (2007) Immune stimulation and improved infection resistance in European sea bass (*Dicentrarchus labrax*) fed mannan oligosaccharides. Fish Shellfish Immunol 23:969–981

Torrecillas S, Makol A, Caballero MJ, Montero D, Ginés R, Sweetman J, Izquierdo M (2011) Improved feed utilization, intestinal mucus production and immune parameters in sea bass (Dicentrarchus labrax) fed mannan oligosaccharides (MOS). Aquacult Nutr 17:223–233

Torrecillas S, Montero D, Izquierdo M (2014) Improved health and growth of fish fed mannan oligosaccharides: potential mode of action. Fish Shellfish Immunol 36:525–544

Tukmachi A, Bandboni M (2014) Effects of Saccharomyces cerevisiae supplementation on immune response, hematological parameters, body composition in rainbow trout *Oncorhynchus mykiss* (Walbaum, 1792). J Appl Ichthyol 30:55–61

Villamil L, Reyes C, Martínez-Silva MA (2014) In vivo and in vitro assessment of *Lactobacillus acidophilus* probiotic for tilapia (*Oreochromis niloticus*, Perciformes: Cichlidae) culture improvement. Aquacult Res 45:1116–1125

Waagbø R (2006) Chap. 13 feeding and disease resistance in fish. In: Mosenthin R, Zentek J, Zebrowska T (eds) Biology of growing animal. Elsevier, London, pp 387–415

Waché Y, Auffray F, Gatesoupe F-J, Zambonino J, Gayet V, Labbé L, Quentel C (2006) Cross effects of the strain of dietary *Saccharomyces cerevisiae* and rearing conditions on the onset of intestinal microbiota and digestive enzymes in rainbow trout, Onchorhynchus mykiss, fry. Aquaculture 258:470–478

Walker PJ, Mohan CV (2009) Viral disease emergence in shrimp aquaculture: origins, impact and the effectiveness of health management strategies. Rev Aquac 1(2):125–154

Walton MJ, Cowey CB, Adron J (1984) The effect of dietary lysine levels on growth and metabolism of rainbow trout (*Salmo gairdneri*). Br J Nutr 52(1):115–122

Wang Y-B, Tian Z-Q, Yao J-T, Li W-F (2008) Effect of probiotics, *Enterococcus faecium*, on tilapia (*Oreochromis niloticus*) growth performance and immune response. Aquaculture 277: 203–207

Wilson RP (1994) Utilization of dietary carbohydrate by fish. Aquaculture 124(1–4):67–80

Xie JJ, Liu QQ, Liao S, Fang HH, Yin P, Xie SW, Niu J (2019) Effects of dietary mixed probiotics on growth, non-specific immunity, intestinal morphology and microbiota of juvenile pacific white shrimp, *Litopenaeus vannamei*. Fish Shellfish Immunol 90:456–465

Zuo ZH, Shang BJ, Shao YC, Li WY, Sun JS (2019) Screening of intestinal probiotics and the effects of feeding probiotics on the growth, immune, digestive enzyme activity and intestinal flora of *Litopenaeus vannamei*. Fish Shellfish Immunol 86:160–168

Technology Prioritization for Climate-Resilient Nutritive Fish

Archana Sinha

Abstract

Fish play an important role in human nutrition by providing protein and essential amino acids. They also add vitamins and minerals to the staple food for a nutritious diet. However, the changing climate is one of the most expected threats in providing a continuous supply of micronutrients, but there are opportunities also which accelerate nutritive sensitive fisheries management. The researchers highlighted the potential physical and biological impacts of changing climate on fish nutrition effect on the nutritional quality of the fish. The physical and biological impacts of climate change may affect the nutrition of fish by affecting their nutritional quality. The physical changes include a rise in water surface temperature, sea-level rise, ocean acidification, high salinity, flood, and change in the harvesting sector; however, the biological changes are responsible for changes in the primary production, distribution pattern, and fish pathology. Elevated water temperature may affect physiological processes of the fish, which finally affect the reproduction process of fish and survival of the larvae. Increases in flood frequency show negative impacts on fish feeding and breeding grounds by the destruction of the freshwater ecosystem or may create a positive impact to expand the aquatic habitats for primary production. The intrusion of more saline water into the coastal zone is expected due to rise in sea level which may affect the distribution of fish. The high wind may also impact fish catching and trade activities. These climatic factors limit the availability of fish in the human diet and interfere with food security directly. Therefore, to improve the food security of the globe through the fisheries sector it is mandatory to follow adaptation and mitigation pathways to safeguard this sector. The chapter deals

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with the technology prioritization in fish nutrition and feeds technology to provide climate-resilient nutritive fish for human food security.

Keywords

Climate change · Fish nutrition · Feed technology · Mitigation · Human health

1 Introduction

Aqua food is a major protein and nutrient source for human health across the world. It is also projected as an ideal option for integration, diversification, livelihood, exports, and even tourism (Ayyappan 2020). Records say that the history of aquaculture started in China around 3000 BC. Scientific aquaculture practices started after the detailed study of natural water bodies to understand the species availability, distribution, species composition, growth potential of species, food and feeding, etc. The good quality of water and abundance of fish food organisms are the key factors for the enhancement of quality fish production. The volume of global fish production amounted to 174.6 million metric tons in 2020, up from 148.1 million metric tons in 2010. There is a need for 30–40 million t additional fish production by 2030 to meet the increased population demand. Fish production is expanding significantly because aquaculture is one of the fastest-growing food production sectors. However, its sustainability is at risk due to the predicted climate change impact. The possible climate change impact such as rise in sea level, high temperatures, diseases outbreak, harmful algal blooms, changes in rainfall patterns, salinity variation in sea surface, and severe climatic events may affect the quality fish production system. There are reports which alert the aquaculturists to face the challenge of impact due to changing climate.

It is well-established fact that fish are rich in bio-available micronutrients, such as zinc and iron, deficiencies of which are a global food security concern (Thilsted et al. 2016). Beveridge et al. (2013) strongly emphasized that the nutritional profile and the nutrients provided by fish are of great concern rather than the availability of fish production because the health of animals is significantly influenced by the quality of feed they fed. Several studies have been conducted to standardize the nutrient requirements of fish for their better growth and biochemical composition. Maire et al. (2021) observed that climate change threatens micronutrient fisheries yields in about 40% of the countries. The populace of countries having low and middle income groups are advised to adopt dietary shift by increasing consumption of nutrient dense food to achieve the target of Sustainable Development Goal 2 (SDG 2) regarding malnutrition and Zero Hunger by 2030 (Kwasek et al. 2020). In addition to the feed available to aquatic animals, several environmental implications ensure sustainable delivery of greater quantities of food (Asche et al. 2008), and water supplies are one of the major concerns (Verdegem and Bosma 2009). The impacts of climate change expect uncertainty about the primary source of

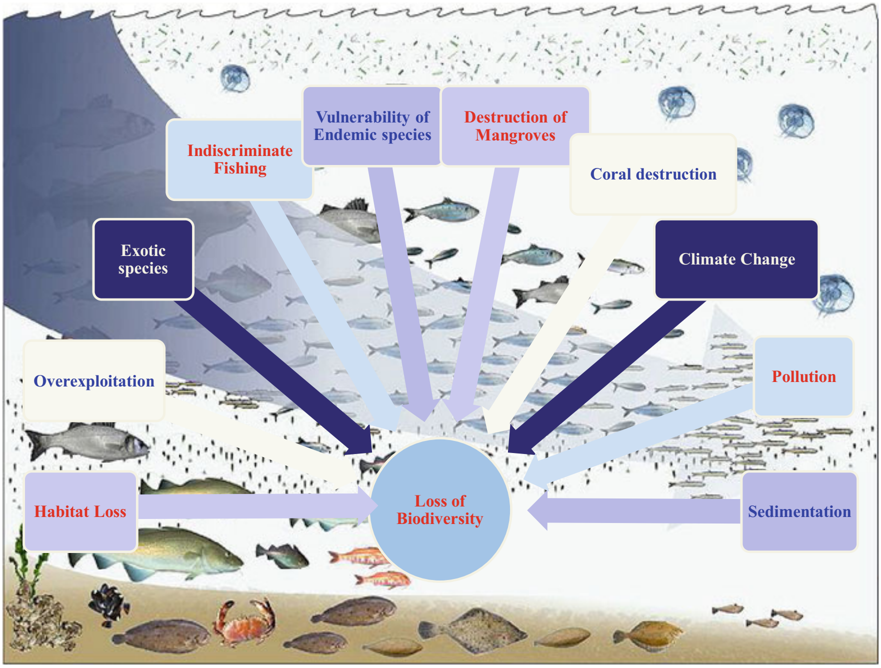

Fig. 1 Biodiversity loss due to environmental degradation

production potential in the future, along with nutritional security (Parry et al. 2005; FAO 2008; Cochrane et al. 2009).

The loss of marine habitats and species is reported due to sudden temperature rise and acidification of the sea (Fig. 1). The shift in ocean currents and rises in water temperature are responsible to change the distribution pattern of fish stocks and alter the structure of ecosystems. It is also documented that the impact of rising global temperatures may equate the reductions in aquatic food availability, limiting minerals like iron and zinc, vitamin B12, and omega-3 fatty acids to mankind.

The nutritive value of food gets lost due to rising greenhouse gas levels which make our food less nutritious. It is mandatory to develop and demonstrate climate-resilient adaptation strategies and sensitize the fishers for increasing their adaptive capacity in the context of changing climate. It is expected that climate change may tend to affect the type, amount, and nutrient quality of food. It is also studied that the increase in temperature and CO2 levels can reduce the nutrient density of some staple food. Coldwater fishes like Salmon and trout depend on cold, oxygenated waters to survive and therefore they are more vulnerable to climate change. The aquatic habitat gets directly impacted by climate change due to warming up the freshwater streams and ocean acidification which results in a toll on the food they depend on. The fishes from larger water bodies like oceans and rivers will be able to migrate towards the more suitable zone, which is not feasible in ponds and wetlands. Climate change is causing devastating effects on inland open fisheries, especially floodplain wetlands, viz. declining natural fish fauna, altering the breeding phenology, and increasing the vulnerability of the ecosystem and dependent fishers.

Fish provides essential nutrition to people around the world, but the changing climate conditions are responsible to impact the nutritive value of fish. Due to the absorption of more CO_2 from the air by the ocean, the pH level decreases to make water more acidic. The available carbonate ions decrease which is used in building shells or skeletons for crabs, corals, oysters, clams, pteropods, etc. These aquatic animals constitute the life of oceans and if their populations decrease it would disrupt the entire marine food web. In contrast, fish are not shelled, however, a slight increase in acidity results in acidosis, abnormal growth, and impairment of their physiology. Freshwater fish can also be impacted by an imbalance in pH levels due to acid rainfall. Marine life is always threatened because climate change affects the waters in which fish live making them more acidic. Porteus et al. (2018) *published* the findings on the threats posed by ocean acidification on fish. The elevated CO_2 levels are responsible to alter responses to sensory cues of marine fishes. The increased CO_2 levels cause loss of hearing in fish due to which they cannot feel their predators and become a victim. It is explained that there is the possibility that the carbon dioxide impacts the nervous system of fish and changes the way that information is relayed to their brains. The change in CO_2 level affects the overall fish population structure, which depends on the time taken for the adaptation of different species in the climate-changing environment. Fishes are cold-blooded poikilothermic animal and the increase in temperature causes change in their habitats. Water temperature affects metabolic processes, oxygen demand, behavior, migration, growth, reproduction, and survival of the fish at a given location. Within the suitable thermal range, an increase in temperature may favor faster growth rates and linger growing season. It is imperative to prioritize the technology identified through the technology scouting process as per the country's needs because all the technologies may not be equally suitable and implementable for climate-smart sustainable fish production. Therefore, detailed studies are required to combat the impact of climate change fish on growth and quality.

2 Nutritional Requirements of Fish

The proximate composition is one of the indicators to study the nutritional value of fish. The principal components of fish are moisture, protein, fat, ash, and carbohydrate. Other constituents also include vitamins and minerals such as iron, zinc, iodine, magnesium, and potassium. These components have been shown to fluctuate with the change in environmental parameters. The edible portion of fish also contains a good source of omega-3 fatty acids which are very important for human health due to their therapeutic role in reducing certain cardiovascular disorders. Fish is also rich in calcium and phosphorus. Like all living beings, fish also require nourishment to maintain their growth and biochemical composition for better survival. They fulfill their requirement either by consuming the natural food available in the habitat or artificially manufactured feed. Different fishes have different feeding habits. Some of them feed on plants, i.e. herbivores; some on animals, i.e. carnivores; and the third group derives its nutrition from both plant and animal sources, i.e. omnivores. Some fish feed on plankton during part of their life and also on other larger animals like annelid worms, snails, mussels, clams, crustaceans, insects, etc. Fish generally change their feeding habits depending upon the availability of food and the environment. The nutrient requirement of fish depends on fish species, size, age, quality of feed ingredients, water quality, temperature, availability of natural fish food, feed processing technique, culture and management conditions, etc. For better growth and survival of fish, there is a requirement for an adequate energy level and protein with a balanced profile of indispensable amino acids, lipids, and essential fatty acids. The inclusion of phospholipids, essential minerals, trace elements, and vitamins is also essential for better growth and survival. The studies established that fish require about 40 nutrients, but quantitative requirements of them are established only for a few species. Metabolism of the building blocks of carbohydrates, lipids, and proteins in the diet fulfills the energy requirement of fish. The fish require 10 numbers of essential amino acids (arginine, histidine, isoleucine, leucine, lysine, methionine, valine, threonine, tryptophan, and phenylalanine) but their quantitative requirements are considerably different among different species. The quality of dietary protein is decided by the levels of available amino acids. Lipids are the rich source of energy and provide the required essential fatty acids for phospholipids synthesis which are important structural components of bio-membranes at the cellular and sub-cellular levels. The lipid of fish has low n-3 and high n-6 PUFA. The five most important fatty acids are linoleic acid (18:n-6), linolenic acid (18:n-3), arachidonic acid (20:4n-6), eicosapentaenoic acid (20:5n-3), and docosahexaenoic acid (22:n-6) which are involved in the structure and functions of fish. Most of the marine species deficient in the enzymes are responsible to biosynthesize such fatty acids from their metabolic precursors and therefore there is a requirement of 20:5n-3 and 22:6n-3 in their diet. Coldwater fish have higher levels of n-3 fatty acids, while warm water fish contains higher n-6 fatty acids. Marine fish have higher n-3 with 20 and 22 carbon PUFA and lower n-6 than freshwater. Although there are species, with specific EFA requirements, the influence of environmental factors is so dominant that the EFA requirement of a single species of fish is changed by variation in temperature or salinity. Simultaneously demersal species contain relatively higher levels of these fatty acids than pelagic ones. Some species especially require a supplement of phospholipids (phosphatidyl choline, phosphatidyl ethanolamine) for metamorphosis, better survival, and growth during the larval and juvenile stages. Most fish tested to require 11 water-soluble vitamins (thiamine, riboflavin, niacin, pantothenic acid, pyridoxine, biotin, folic acid, cyanocobalamin, ascorbic acid, and choline, inositol) and at least three of four fat-soluble vitamins (A, D, E, and K). Most of the minerals and trace elements including calcium, phosphorous, sodium, magnesium, potassium, sulfur, chlorine, iron, copper, cobalt, iodine, manganese, zinc, molybdenum, selenium, fluorine, etc. are absorbed by the fishes from their habitat. However, a diet fortified with mineral and trace elements is essential to sustain their optimum growth. The nutritional requirement of commercial fish is shown in Table 1.

Table 1 Nutritional requirement of common cultivable fish

Fish	Feeding habit	Protein requirement	Fat requirement	Suitable fish feed
Big head carp	Plankton feeder	18–23%	<5%	Water with a high plankton content/peanut cake
Grass carp	Herbivorous	18–23%	<5%	Grass/low protein dry pellet feed
Scat	Omnivorous	24–33%	5–6%	Dry pellet feed of medium protein content
Rabbitfish	Omnivorous	30%	5%	Dry pellet feed of medium protein content
Sea bass	Carnivorous	38–42%	6–10%	Dry/moist pellet feed/trash fish
Grouper	Carnivorous	Above 45%	Above 10%	Dry/moist pellet feed/trash fish
Seabream	Carnivorous	40–45%	>5%	Dry/moist pellet feed/trash fish

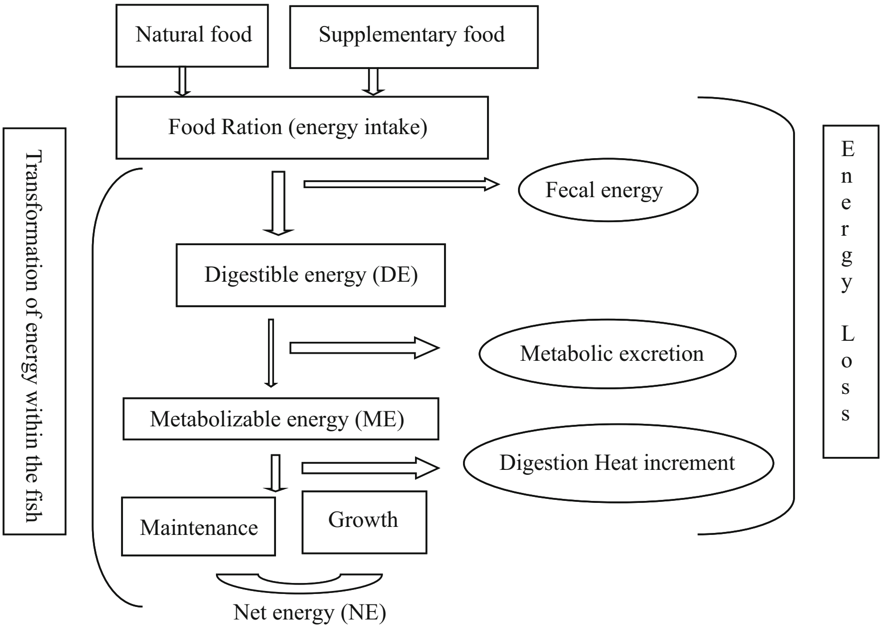

Fig. 2 Energy flow in fish metabolism

Digestion of ingested food is done by the digestive enzymes, the released nutrients are then absorbed by the gut and the undigested materials are excreted as feces (Fig. 2). The process depends on different climatic conditions as well as types of food.

3 Existing Practices of Feed Management and Scope of Upscaling

Existing systems of fish production evolve greenhouse gases (GHG) as different levels of carbon footprints which affect the environment adversely. The mean increase in global temperature and change in weather patterns are responsible for global climate change. Fish feed, feeding management, and feeding strategies are the most important issue for sustainable fish production. FAO (2009) has shown concern by mentioning that the intensification of present aqua production systems affects the health of the animal and their safety. The principle of fish feed management includes the selection of the right type of feed, applying a suitable feeding method, focusing on feeding cost, etc. In common fish culture systems, the naturally available food has a major role in the different life stages of fish. It is recommended to promote the growth of natural food as much as possible and use artificial feeds as a supplement only in unavoidable conditions. The fish need more nutrition as they grow older and their environment can fulfill the requirement, especially under intensive production conditions, and in that case, they should be given nutritionally complete prepared feeds. In different culture systems like raceways, cages, pens, and re-circulating systems, the natural food is minimal and therefore the use of nutritionally complete prepared feed is critical. In existing aquaculture practices there are three types of food used: natural food, supplementary feeds, and complete feeds. Based on the type of food given to the fish the production system is defined as extensive (depends entirely on natural food), semi-intensive (depends on supplementary feed), and intensive (depends entirely on complete feed). Environmental protection is the key to the sustainable development of resources, particularly natural resources. Proper planning and enforcement of regulations are required for the same with appropriate adoption of technologies. There is ample scope to upscaling fish nutrition management in light of climate change threats.

4 Temperature Rise Impact on Fish Physiology

The basic of fish nutrition depends upon the application of biochemistry and physiology of the animal. Hence, a thorough knowledge of biochemistry and physiology is the pre-requite to understand fish nutrition in changing climate. Temperature is known to affect the enzyme reaction, immune response, hematological parameters, and plasma electrolyte. The physiological process of fish is temperature-dependent and the temperature rise accelerates most of the activities during the process. The oxygen consumption increases two to threefolds by an increase of temperature of about 10 °C. Temperature fluctuation is a severe problem related to the growth, reproduction, site selection, and migration of many fishes. Mainly anadromous fishes like hilsa are badly affected by these factors. Disruption of rainfall due to changed weather conditions hampers the reproductive behavior of many fish. Once the critical temperature level exceeds for the fish, it leads to growth cessation, anaerobic respiration, protein denaturation, permanent inactivation of enzymes, and eventual death. As oxygen is essentially required for the oxidation of absorbed food energy nutrients, the temperature increase causes an increased metabolic rate resulting in increased demand for nutrients. The process thereby enhances food intake and finally grows up to the temperature optima. The temperature also affects enzyme function Somero (1978). Some enzymes that are linked with the process of energy release (enzymes of glycolysis, pentose shunt, tricarboxylic acid cycle, electron transport, and fatty acid oxidation) exhibit temperature compensation, whereas those enzymes dealing largely with the degradation of metabolic products show poor or reverse compensation (Prosser 1973). The increase in temperatures may result in lower levels of HUFAs especially EPA and DHA (Kheriji et al. 2003). Kemp and Smith (1970) studied the fatty acid composition of goldfish adapted to different temperatures and observed that temperature was not a key factor to affect the fatty acid composition of the whole-fish lipids, but there were marked changes in the fatty acids of lipids that are extracted from homogenates of goldfish intestinal mucosa which were more pronounced in a membrane fraction. The fatty acids of choline and ethanolamine phosphoglycerides are more susceptible to the changes made by temperature than the phosphoglycerides of inositol or serine. Carp undergo temperature acclimation of respiratory function by altering mitochondrial ATP synthase (Fo F1 -ATPase) both quantitatively and qualitatively (Itoi et al. 2003).

5 Smart Practices and Technologies for Climate-Resilient Fish Production

Under the Hi-Tech System of aquaculture, a well-balanced diet and adequate feeding are two important aspects of maintaining a perfectly hygienic and congenial aquatic environment. In the changing scenario of global climatic conditions, a change is also expected in thinking of ways and solutions to adaptation and mitigation of climate change impact on fish production (Free et al. 2019; García Molinos 2020). It is forecasted that the productivity of global marine fisheries will decline; however, Free et al. (2020) found that climate-adaptive fisheries management practices could help to protect production by ameliorating many of the adverse climate change impacts on livelihood and nutritional security. Appropriate steps should be a plan at right time to mitigate the climate-induced changes in individual stock distributions and in the portfolio of stocks available at any given time in any given place.

5.1 Natural Farming System

Natural farming may define as a chemical-free traditional farming system. It is an agro-ecology-based diversified culture system that integrates crops, trees, livestock, and fisheries with functional biodiversity. An integrated farming approach helps to conserve agro-biodiversity, provides food security, enhances ecosystem services, maintains environmental quality, and ensures sustainability. Under the changing scenario of Indian aquaculture, intensification and application of artificial feed are significant functional trends. Feed-based intensive culture system is becoming more popular than manure-based extensive aquaculture. The inclusion of additional nutrients in the form of artificial feed enhances the probability to degrade the soil quality and subsequently affects the productivity of an ecosystem.

5.2 Utilization of Open Water and Enclosure

Global warming is one of the key factors that can alter the marine zooplankton and crack the food web which impacts the sustainability of fisheries and aquaculture (Harley et al. 2001). Temperature increase and acidification of the ocean are the limiting factors for calcification which disturbs marine species such as shrimp and corals in forming their shells (Khoshnevis and Shakouri 2010). Simultaneously, increased stratification, reduced primary productivity, decreased mixing of water in lakes, and supply of food result in reductions in fish stocks (Coe and Foley 2001). Detoriated water quality especially having low dissolved oxygen level changes the range and abundance of pathogens, predators and competitors by giving a way to invasive species. Global warming can lead to disease outbreaks and high aeration requirements in aquaculture systems (Hall 2011). Increased temperature, enhanced oxygen demand, and decreased pH reduce the precipitation and increase evaporation that threat many inland fisheries systems. Development and testing of technology to combat the climate change impact on open water aquatic ecosystem is the demand in coming days.

Cage Culture

Cage culture in open waters is an adaptation option to enhance fish production in controlled conditions (Fig. 3). The technology can be adopted under various agro-climatic conditions. The changing climate may impact the quality of fish in natural conditions by affecting their preferred food resulting in low productivity. The scope of cage culture in inland and marine water is relevant in enhancing fish production by selecting the right species, location, and cage specification including size and material, improved feed, and health management. Cages are used for rearing fish in a volume of water enclosed on all sides with netting materials including the bottom and free circulation of water is permitted through the mesh of the cage. The selection of species for cages should be customized based on economic and nutritional value, regional preferences, market demand, hardiness, and tolerance to the changing climate. The striped catfish *Pangasianodon hypophthalmus* has achieved great importance as a candidate species for cage culture in India. The species cultured in cages in marine and brackishwater are *Lates calcarifer*, cobia (*Rachycentron canadum*), *Mugil cephalus*, and *Etroplus suratensis*, whereas in freshwater cages *Labeo rohita*, *Cirrhinus mrigala*, *Pangasius* sp., *Channa* sp., and *Heteropneustes fossilis* are being cultured. The supplementary feed of floating nature is one of the important requirements for cage culture and therefore, cost-effective,

Fig. 3 Fish culture in cages at Chandil reservoir of Jharkhand, India

environmentally friendly nutritionally balanced feed is essential for cage culture practices.

Pen Culture

Pen culture is a type of enclosure culture and has the advantage of providing natural food base for the fish. The institute has undertaken climate-resilient pen systems in wetlands of West Bengal, Assam, and Kerala for farming of fish and shellfish and conservation of SIFs. The climate-resilient pen systems (CRPS) and cage systems (CRCS) have high tensile strength HDPE net material, provision to withstand flood, and wind action and is used for culturing resilient indigenous species. Stocking of climate-resilient indigenous fish species is encouraged in pens and cages to adapt to changing climate. The installation of a climate-resilient pen culture system (CRPS), distribution of high-protein feed for fish growth, and stocking of climate-resilient indigenous fishes in CRPS is the need of the day.

Canal Culture

Fish culture in irrigation canals is one of the recent concepts for maximum utilization of water (Fig. 4). In Egypt, about 16% of freshwater fish production comes from the river Nile and its associated irrigation canals, while the fish biomass in minor canals of Geizira irrigation system is recorded at an average production of approx 660 kg/ha in Sudan. The practice of releasing *Oreochromis spp., Channa striatus,* and *Puntius*

Fig. 4 Fish culture in canals of Indian Sundarbans

gonionotus into irrigation canals without supplementary feed resulted in 350 kg/ha in Thailand (Anon 2003). The irrigation canals exhibit lower species diversity than the nearby static water bodies which is influenced by changing temperature and fewer primary producers (Tarplee Jr. et al. 1971; Daget 1976; Anon 1990). The extensive culture of carp and Nile tilapia in irrigation canals has been successfully demonstrated in Thailand (Little and Muir 1987). Physicochemical parameters in canals are strongly correlated with the phytoplankton abundance (Napiorkowska-Krzebietke 2014; Bishnoi et al. 2013). Matta (2015) reported that NO_2, NO_3, SIO_3, HCO_3, PO_4, Ca, and Mg are the important variables in the shaping of benthic assemblage in the Upper Ganga Canal; zooplankton is primarily dominated by rotifers, cladocerans, and protozoans in Ganga Canal (Bishnoi and Sharma 2016). Commercially cultured species in enclosures include carps, tilapias, catfishes, snakeheads, and pangasiids, all of which may be suitable for culture in irrigation canals. Fish could be profitably and successfully reared in irrigation canals to control unwanted aquatic weed growth. Grass carp *Ctenopharyngodon idella* is the most suitable example, it is an effective weed control agent as well as a popular food fish. Tilapias are perhaps the most versatile species, especially where derelict, high-salinity waters are concerned, although their escape into the canals and associated waters could be damaging. It is also, along with Chinese and Indian carp, more suited to extensive and semi-intensive production techniques. Snakeheads and catfish are carnivorous and would, therefore, require more expensive high-protein feeds. Freshwater prawns (*Macrobrachium* spp.) should also be considered for culture in slow-moving canals. Habitats within a canal may not be suited to the endemic species of the area as there may be a lack of breeding sites, stimulants to breeding, or the correct food. Therefore, the possibility of using indigenous fish, rather than the other introductions is always viable in canal culture (Sinha et al. 2022b).

6 Integrated Farming System

Global warming is accelerated by the emission of greenhouse gases from industries, burning of fossil fuels, agricultural activities including deforestation, burning of residue, etc. A climate-smart integrated farming system including crops, vegetables, livestock, and fisheries as a whole-farm approach is the best technology for sustainable food production. In this system waste from one production component is used by the other one to reduce the input cost and ensure an overall increase in productivity. The technology of new integrated farming methods includes integrated nutrient management, application of bio-fertilizers, and crop rotation. Aquaculture provides opportunities to mitigate climate change impact by integrating aquaculture and agriculture. Water from aquaculture ponds can help sustain crop productivity during periods of drought, while at the same time the nutrient-rich waters can increase productivity. Taking advantage of the short generation time and high fecundity, it would be possible to selectively breed fishes to tolerate higher temperatures, salinity, and increased diseases that are likely to impact aquaculture due to climate change. Aquaculture depends heavily on capture fisheries for fish meal and in certain areas for seed hence there is an urgent need to find plant protein-based alternatives to fish meal and for domestic species for which there is still a dependence on wild broodstock. To meet climate change there is a greater emphasis on renewable energy like offshore wind, wave, and tidal energy and greater nuclear power capacity being proposed with coastal or inland water cooling and these can adversely affect coastal and inland aquaculture unless strategies to mitigate their effect are inbuilt.

To adapt to sea-level rise, the agri-aqua farm should be promoted. Seawater can be converted into potable water through mariculture cum agro-forestry involving mangroves *Salicornia, Atriplex, Sesuvium,* and *Casuarinas*. Coastal aquaculture is an important component of seawater farming, thereby opening up new windows of opportunity for using seawater as an important sector for sustainable food and nutrition security systems.

7 Re-Circulatory Aquaculture System (RAS)

Re-circulating aquaculture systems (RAS) are intensive tank-based culture system that facilitates water reuse using different treatment steps. A series of treatment processes are utilized to maintain water quality in intensive fish farming operations. A typical RAS unit (Fig. 5) consists of a culture tank, along with a solid removal unit followed by a nitrogen removal and disinfection unit. These units recycle the outlet water from the culture tanks and are circulated back to the culture tank, which reduces the dependence on water and gives almost complete control over the culture system. As a result, the RAS can be used in any part of the world irrespective of the climatic condition (Badiola et al. 2018). This attribute helps in the reduction of CO_2 emission associated with food transport by facilitating the culture of seafood near the market areas (Martins et al. 2010). The research has also proved that the integration of aquaponics in the RAS system can help in the effective utilization of unwanted

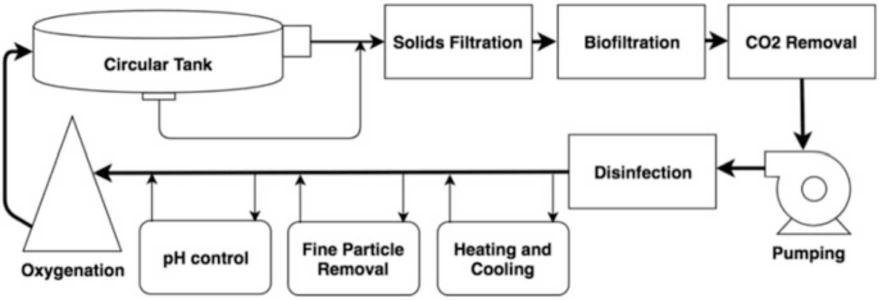

Fig. 5 The water treatment process in RAS

nitrogen from the RAS system and can produce vegetables as an extra output (Calone et al. 2019). However, it is quite cost-effective technology and needs further research in India to conclude which species best suits RAS.

8 Biofloc-Based Aquaculture System

FAO (2020) says that aquaculture despite being the fastest-growing sector globally supports livelihoods and nutritional security to the millions, is vulnerable to climate change, and is of great concern to mitigate the impacts. The fish culture system sector is exposed to climate hazards and sensitive to these changes. Barange et al. (2018) enlisted the climate change impacts such as flood, drought, salinity intrusion, heat waves, sea-level rise, and ocean acidification. Biofloc technology is one of the viable adaptations to culture fish as an option to mitigate climate change impact. The *principle of this technique is the generation of the nitrogen cycle by maintaining a higher C:N ratio* through stimulating heterotrophic microbial growth, which assimilates the nitrogenous waste that can be exploited by the cultured spices as a feed (Fig. 6). Biofloc is having high nutritional value containing 12–50% protein, 0.5–12.5% lipid and 13–50% ash content on a dry weight basis.

Biofloc technology (BFT) has beneficial effects on aquaculture management, including water quality, feeding, and disease control. The application of BFT in aquaculture offers a solution to avoid the environmental impact of high nutrient discharges and to reduce the use of artificial feed. In BFT, excess nutrients in aquaculture systems are converted into microbial biomass, which can be consumed by cultured animals as a food source. This technology, to a certain extent, has also the capacity to control pathogens in the aquaculture system. The main principle of biofloc technology (BFT) is to recycle nutrients and nitrogenous wastes by maintaining a high carbon/nitrogen (C/N) ratio in the water to stimulate the growth of heterotrophic bacteria (Avnimelech 1999). Bacteria growth increases when carbon sources such as molasses, wheat bran, and cellulose are applied in the pond with continuous aeration (Crab et al. 2012). Through maintaining the C/N ratio in the

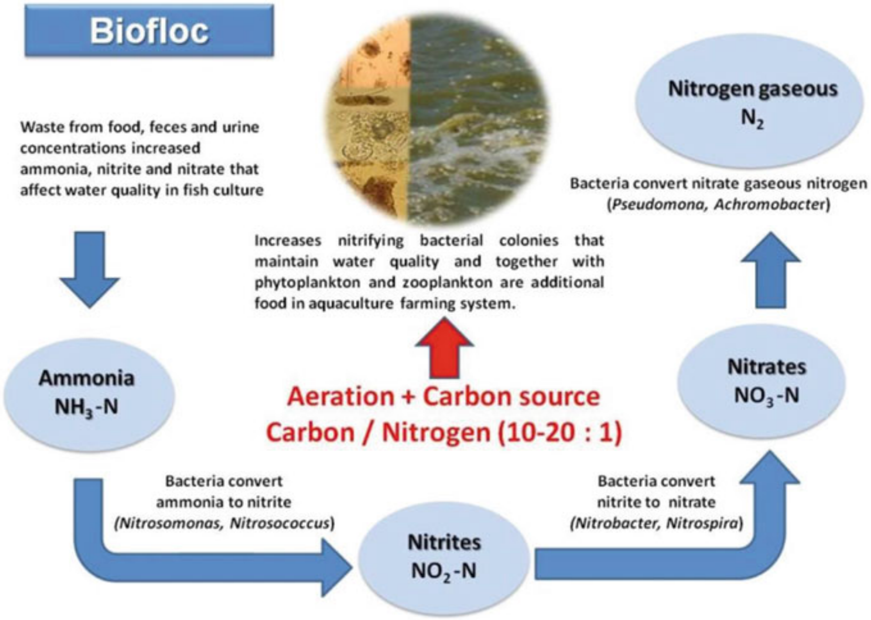

Fig. 6 Steps involved in biofloc-based aquaculture

culture system by adding a carbon source the water quality can be improved along with the production of high-quality single-cell microbial protein, De Muylder et al. 2010. In addition to maintaining the water quality, biofloc also provides essential and better quality nutrition to the shrimp to achieve fast growth, low FCR, and the possibility to prevent diseases (Azim and Little 2008). The promotion of floc formation is influenced by a combination of physical, chemical, and biological interactions such as temperature, pH, dissolved oxygen, organic loading rate, etc. This technology is based on an environmentally friendly approach to reducing pollution and supporting zero/minimal water exchange, recycling in situ nutrients, improving biosecurity, improvement of FCR by augmenting natural food, providing a stress-free environment, and eliminating antibiotics and chemicals. Anand et al. (2014) elucidate the suitability of biofloc as dietary supplementation in shrimp feed for enhancement of growth and digestive enzyme activities.

9 Nutrient-Dense Small Indigenous Fish (SIF)

The impact of climate change on wild fish populations is apprehensive and is of great concern because some species require a narrow range of temperature for their reproduction. In addition, researchers are also worried about the temperature rise of water which can lower the oxygen content of water. This is one of the major limitations for the survival of large fish. But the smaller fish has more gill area to

Table 2 Nutrient content of some SIF (Mohanty et al. 2013)

S. no	SIFs	Calcium (g)	Iron (mg)	Zinc (mg)	Vitamin A (mg)
1	*Amblypharyngodon mola*	0.853	5.7	3.2	>1500
2	*Gudusia chapra*	1.063	7.6	2.1	NA
3	*Chanda nama*	0.955	1.8	2.3	100–500
4	*Esomus danricus*	0.891	12	2.1	500–1500
5	*Mystus vittatus*	NA	NA	1.5	100–500
6	*Channa punctatus*	0.766	1.8	3.1	100–500
7	*Puntius chola*	1.171	3.0	NA	<100
8	*Heteropneustes fossilis*	0.042	4.86	NA	<100
9	*Clarias batrachus*	NA	NA	NA	<100
10	*Channa stariatus*	82.20	1.88	NA	NA
11	*Oreochromis niloticus*	585.20	1.5	NA	NA
12	*Mystus tengara*	190	14.5	17.0	NA

acquire oxygen, relative to its body size, than a large fish. If the large species cannot migrate easily to cooler waters, there is a possibility that their ecological communities will end up and small fishes will dominate which could be a real problem for the local fishing industry. Maintaining reproductive potential and stability of a fish population and its size play an important role. The larger individuals tend to produce more eggs of better quality (Hsieh et al. 2010; Hixon et al. 2014) and have a longer spawning season (Berkeley and Houde 1978; Sogard et al. 2008). Trippel et al. (1997) and Vandeperre and Methven (2007) observed that small and large individuals may spawn at different sites. Such bet-hedging strategies provide resilience capacity for populations to sustain in unfavorable climatic conditions (Ripa et al. 2010). Hence, a suitable size structure of fish may provide a resilient option to maintain the fish population. There are some nutrient-dense small species ubiquitous in all the natural water bodies and less vulnerable to the impacts of climate change and overfishing are the potential target species in climate-resilient fisheries management. SIF is a better source of animal protein for human nutrition. Mohanty et al. (2013) have documented the nutritional value of these fish. The details are mentioned in Table 2.

Small indigenous fish (SIF) is climate-resilient species and naturally breeds in inland water at relatively short time intervals. Most of the SIFs are tolerant of relatively poorer water qualities compared to major carp and catfishes. The small fish is an important food item as an animal protein source in the diet of a rural community. Though the Indian aquaculture system is carps based it is well documented that poor rural people often consume locally available small fish instead of carps. These small indigenous fish (SIF), having a length of about 25 cm is locally available in the small water resources, viz. wetlands, canals, streams, etc., and are affordable to the poor people also. The role of SIF in providing micronutrients to the human being is valuable, especially where deficiency of micronutrients is a critical problem. This fish although bred naturally is responsive to conducive conditions of the habitat; due to environmental degradation, their propagation is dwindling in recent times (Sinha et al. 2022a). A high-priced food fish now calls for its conservation, propagation in temporary water resources, paddy fields, etc. to harness extra benefit from such resources by the farmers. Roos et al. (1999) highlighted the importance of self-recruiting species (SRS) in natural as well as managed habitats of aquaculture to support global nutritional security. A considerable number of small indigenous fish along with introduced fish species are always present in almost all the aquatic resources unless they are not deliberately eradicated. A study shows that 62% of SIFs are highly resilient (in which the population doubles in 2 years or less) and 38% are medium resilient (with a population doubling time of above 5 years) (Sarkar and Lakra 2010). There are good numbers of high-demand SIF species that can be cultivated and introduced as candidate species to diversify the aquaculture system under extreme weather conditions. These are identified as *Amblypharyngodon mola, A. microlepis, Puntius ticto, Notopterus notopterus, Puntius sarana, Danio devario, Chanda nama*, *Labeo bata, Cirrhinus reba, Salmostoma bacaila, Nandus nandus, Anabas testudineus, Esomus danricus, Puntius chola, Glossogobius giuris,* etc.

10 Climate-Resilient Species Diversification

Rapid climate change posed concerns over the ecological systems and aquaculture. Generally, the conventional aquaculture system is dependent on carp, catfishes, prawns, and shrimps. They adapt themselves in their aquatic habitat. However, in changing extreme weather conditions the availability of these fishes is declining drastically. There are some other important non-commercial fish that are sturdy and dominate the same water body by suppressing the diversity of commercially important fish. To mitigate the climate change impact on fish diversification, it is one of the important options to include eco-friendly and regionally adopted fish species to boost the intensification of integrated agriculture with fisheries. A significant number of such fishes are a rich source of nutrition for the rural poor or a delicacy for the rich. The detailed documentation and conservation of climate-resilient fish fauna which are an important components of the biosphere are essential both for maintaining equilibrium in the natural biota and sustainable development as well as maintenance of the food chain. Air-breathing fish that are more able to withstand many of the expected impacts of climate change such as increased water temperatures and deteriorated water quality may come under the category of climate-resilient species. Small indigenous fish (SIF) like mola (*Amblypharyngodon mola*), puti (*Puntius sophore, P. ticto, P. chola*), darkin (*Esomus danricus*), etc. are also identified as climate-resilient species. Catfishes, namely *Clarias magur* and *Heteropneustes fossilis* are high valued climate-resilient species that can be cultured at very high stocking densities. Minor carps like *Labeo bata* and *L. gonius* could tolerate low temperatures in enclosure cultures.

11 Fish Feed Manufacturing and Management

The nutritional value of fish depends on the quality of feed they fed. To maintain the nutrient composition of fish in changing climatic scenarios, there is a need to develop feed accordingly. The knowledge about changing patterns both metabolic needs and feeding behavior due to climate change is necessary to develop proper feed and feeding strategies.

No doubt, live fish food plays a major role in maintaining the fish quality both in a natural and managed environments. Zooplankton fulfills the nutritional requirement of the larva as well as controls the deterioration of water quality. There is a strong need to develop cultural technology for zooplankton like cladocera and copepod. As the culture systems are getting more and more intensified, the need for artificial feed is increasing accordingly. It may be applied as supplementary feed or complete feed based on the intensification of the culture system. The application of artificial feed has a direct impact on the environment as the waste food may pollute the water. Therefore, the selection of feed ingredients and the process of manufacturing the feed need more research to select the best feed technology for climate change mitigation. Several feed additives and stimulants are recommended for the best utilization of feed in the different culture systems and different climatic condition. Some feed additives like binders, attractants, coloring agents, antioxidants, or medicine (antibiotics, other growth stimulants, etc.) should be added as per the requirement. Addition of pigments like β-carotene, canthaxanthin, and astaxanthin in the diet increases skin coloration and viable egg production in ornamental fish.

11.1 Nutrizymes

Nutrizymes are nutraceuticals from exogenous enzymes, which increase the digestibility of feed ingredients and subsequently enhance the growth of the animals. Supplementation of exogenous digestive enzymes such as proteinase and amylase improves the nutritional digestibility of the fish. Fish cannot secrete the enzyme xylanase and therefore it must be added to the feed for better digestibility of the ingredients. Supplementation of exoenzymes will increase weight gain, improve plumpness, reduce feed variation, increase output per unit area, and prevent environmental pollution.

11.2 Probiotics

Probiotics is a live microbial feed supplement that beneficially affects the host animal by improving its intestinal microbial balance. The species which are commonly used in probiotics preparation are *Lactobacillus bulgaricus, L. acidophilus, L. sporogenes, L. casei, L. salivarius, L. Plantarum, Streptococcus thermophilus, Enterococcus faecalis*, etc. Feed probiotics can be administered through feed and finally find their way into the gut or gastrointestinal tract of the cultured organisms.

They can be incorporated into artificial feed as a supplement and also used as enriched media to culture the live fish food organism known as bio-encapsulation. Commercially prepared probiotics are also available on the market in different brands. The result of the application of probiotics in feed management practices of fish culture is promising.

11.3 Prebiotics

Prebiotics are compounds in food that induce the growth or activity of beneficial microorganisms such as bacteria and fungi. The most common example is in the gastrointestinal tract, where prebiotics can alter the composition of organisms in the gut microbiome. These are associated with improvements in growth, feed efficiency, gut microbiota, digestive enzyme activities, gut morphology, immune status, disease resistance, intermediary metabolism, and stress responses.

11.4 Microalgae

Microalgae are potential fish feed ingredients because the cell metabolites of microorganisms contain a blend of essential amino acids, healthy triglycerides, vitamins and pigments. Microalgae cultivation requires a constant supply of several inorganic nutrients, such as nitrogen (N), phosphorus (P), and potassium (K) to maintain high algae yields (Fig. 7). It has been demonstrated that a combination of two microalgal species, *Nannochloropsis oculata*, and *Schizochytrium* sp., can be

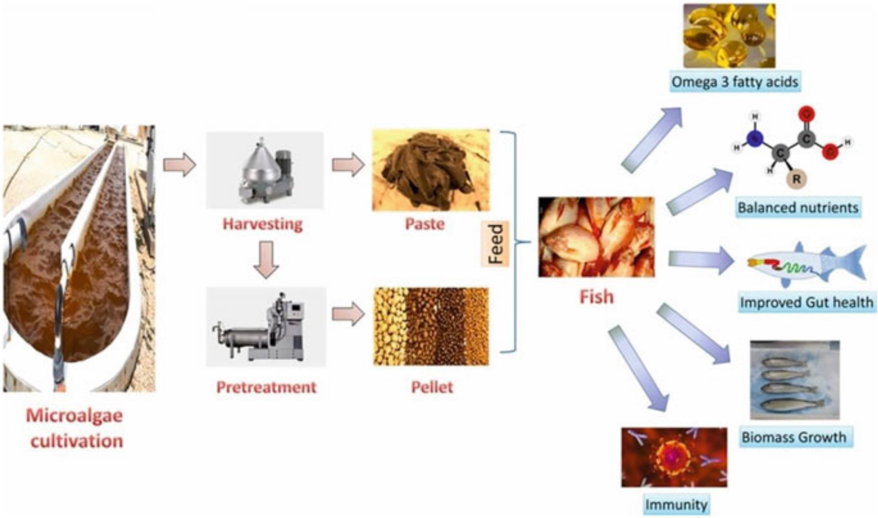

Fig. 7 Processing and utilization of microalgae as fish feed

used to feed Nile tilapia (*Oreochromis niloticus*), the second-largest farmed fish in the world.

Methods of processing and preparation of artificial diets and potential contamination of components by environmental changes are of great concern. The demand and automatic fish feeding equipment are advantageous over manual feeding practices. Manual feeding involves not only manpower but also leads quite often to overfeeding resulting in wastage of food and causing environmental pollution.

12 Conclusions

Ongoing global warming and climatic changes are becoming the most serious environmental issues. Only an increase in a few degrees of temperature may cause detrimental problems to animals, especially to poikilotherms like fish. The food and feeding habits of fish are directly related to their habitat. Most of the fish prefer live feed available in the ecosystem. But climate change is impacting water level, temperature, salinity, pH, and other physicochemical parameters of the fisheries resources. The fast changes in the aquatic ecosystem affect the preferred food of fish. The climatic variability has altered the quantum of plankton communities which implicated their growth rate, biomass, and diversity in aquatic water bodies. Fish can adapt themselves to environmental changes below the critical level. Migration of fish is one of the adaptive features of fish. But they do not face the critical change impact and suffer resulting slow growth rate, declining population size, denatured proximate composition, and eventually death. To mitigate the climate change impact on fish which are an important source of protein, lipid, and vitamins for human nutrition, studies are invited to develop technology accordingly to maintain the quality of fish. Prioritization is to maintain the natural fish food organism, judicious use of feed ingredients, environmentally friendly aquaculture, application of feed supplements, and selection of nutrient-dense climatic resilient fishes for culture. The increase in fish production is very important but it is more important to produce high-quality fish for the nutritional security of the globe.

References

Anand PSS, Kohli MPS, Kumar S, Sundaray JK, Dam RS, Venkateswarlu G, Sinha A, Pailan GH (2014) Effect of dietary supplementation of biofloc on growth performance and digestive enzyme activities in *Penaeus monodon*. Aquaculture 418–419:108–115

Anon (1990) Fish production in irrigation canals—a review. FAO Fish Tech Pap No. 317, Rome, p 111

Anon (2003) Fisheries in irrigation systems of arid Asia, FAO Fish Tech Pap No. 430, Rome, p 150

Asche F, Roll K, Tveteras S (2008) Future trends in aquaculture: productivity growth and increased production. In: Holmer M, Black K, Duarte CM, Marba N, Karakassis I (eds) Agriculture in the ecosystem. Springer, Berlin, pp 271–292

Avnimelech Y (1999) Carbon and nitrogen ratio as a control element in aquaculture systems. Aquaculture 176:227–235

Ayyappan S (2020) Drivers of aquaculture development in India. In: Sugunan VV, Suresh VR, Murthy CK (eds) Indian Aquaculture. Society for Indian Fisheries and Aquaculture, Hyderabad, pp 1–9

Azim ME, Little DC (2008) The biofloc technology BFT in indoor tanks: water quality, biofloc composition, and growth and welfare of Nile tilapia *Oreochromis niloticus*. Aquaculture 283: 29–35

Badiola M, Basurko OC, Piedrahita R, Hundley P, Mendiola D (2018) Energy use in recirculating aquaculture systems (RAS): a review. Aquacult Eng 81:57–70

Barange M, Bahri T, Beveridge MC, Cochrane KL, Funge-Smith S, Poulain F (2018) Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. In: FAO fisheries and aquaculture technical paper (FAO) eng no. 627 (ISBN 978-92-5-130607-9)

Berkeley SA, Houde ED (1978) Biology of two exploited species of halfbeaks, *Hemiramphus brasiliensis* and *H. balao* from southeast Florida. Bull Mar Sci 28:624–644

Beveridge MC, Thilsted SH, Phillips MJ, Metian M, Troell M, Hall SJ (2013) Meeting the food and nutrition needs of the poor: the role of fish and the opportunities and challenges emerging from the rise of aquaculture. J Fish Biol 83(4):1067–1084. https://doi.org/10.1111/jfb.12187

Bishnoi RK, Sharma BK (2016) Planktonic variations in a lotic water body of Shri Gangasagar District, (Rajasthan). Int J Fauna Biol 3(1):134–139

Bishnoi RK, Sharma BK, Durve VS, Sharma LL (2013) Primary productivity in relation to planktonic biodiversity in a stretch of Ganag Canal (Rajasthan). Univ J Environ Res Technol 3(2):266–272

Calone R, Pennisi G, Morgenstern R, Sanyé-Mengual E, Lorleberg W, Dapprich P, Winkler P, Orsini F, Gianquinto G (2019) Improving water management in European catfish re-circulating aquaculture systems through catfish-lettuce aquaponics. Sci Total Environ 687:759–767

Cochrane K, De Young C, Soto D, Bahri T (2009) Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. In: Fisheries and aquaculture technical paper no. 530. FAO, Rome

Coe MT, Foley JA (2001) Human and natural impacts on the water resources of the Lake Chad basin. J Geograph Res 106:3349–3356

Crab R, Defoirdt T, Bossier P, Verstraete W (2012) Biofloc technology in aquaculture: beneficial effects and future challenges. Aquaculture:351–357

Daget J (1976) La production de poisson de consummation dansles ecosystem irrigues. In: Worthngton EB (ed) Arid land irrigation in developing countries-environmental problems and effects. Pergamon Press, London, pp 295–301

De Muylder E, Claessens L, Herizi M (2010) Production of shrimp *Litopenaeus vannamei* without marine proteins in a biofloc system. In: Biofloc Production-Aquafeed Winter2010 Publication. Aquafeed Magazine., pp 1–3

FAO (2008) Climate change and food security: a framework document. Food and Agricultural Organization of the United Nations, Rome

FAO (2020) The state of world fisheries and aquaculture 2020. FAO, Rome. (ISBN: 978-92-5-132692-3)

FAO (Food and Agricultural Organization) (2009) How to feed the world in 2050. FAO, Rome. http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf

Free CM, Thorson JT, Pinsky ML, Oken KL, Wiedenmann J, Jensen OP (2019) Impacts of historical warming on marine fisheries production. Science 363:979–983. https://doi.org/10.1126/science.aau1758

Free CM, Mangin T, Molinos JG, Ojea E, Costello C, Gaines SD (2020) Realistic fisheries management reforms could mitigate the impacts of climate change in most countries. PLoS One 15:e0224347. https://doi.org/10.1371/journal.pone.0224347

García Molinos J (2020) Global marine warming in a new dimension. Nat Ecol Evol 4:16–17. https://doi.org/10.1038/s41559-019-1037-5

Hall SJ (2011) Climate change and other external drivers in smallscale fisheries: practical steps for responding. In: Small scale fisheries management: frameworks and approaches for the developing world. CAB International, Cambridge, pp 132–159

Harley HCD, Hultgren RA, Miner KM, Sorte BG, Thornber CS et al (2001) The impacts of climate change in coastal marine systems. Ecol Lett 9(2):228–241

Hixon MA, Johnson DW, Sogard SM (2014) BOFFFFs: on the importance of conserving old-growth age structure in fishery populations. ICES J Mar Sci 71:2171–2185. https://doi.org/10.1093/icesjms/fst200

Hsieh CH, Yamauchi A, Nakazawa T, Wang W-F (2010) Fishing effects on age and spatial structures undermine population stability of fishes. Aquat Sci 72:165–178. https://doi.org/10.1007/s00027-009-0122-2

Itoi S, Kawahara S, Kondo H, Sakai T, Watabe S (2003) Changes in mitochondrial fatty acid composition following temperature acclimation of carp and their possible effects on Fo F1 -ATPase activity. Fish Physiol Biochem 29(3):237–224

Kemp P, Smith MW (1970) Effect of temperature acclimatization on the fatty acid composition of goldfish intestinal lipids. Biochem J 117(1):9–15. https://doi.org/10.1042/bj1170009

Kheriji S, El-Cafsi M, Masmoudi W, Castell JD, Romdhane MS (2003) Salinity and temperature effects on the lipid composition of mullet sea fry (Mugil cephalus, Linne, 1758). Aquac Int 11(6):571–582

Khoshnevis YS, Shakouri B (2010) The effects of climate change on aquaculture. Int J Environ Sci 1(5):378

Kwasek K, Thorne-Lyman AL, Phillips M (2020) Can human nutrition be improved through better fish feeding practices? a review paper. Crit Rev Food Sci Nutr 60(22):3822–3835. https://doi.org/10.1080/10408398.2019.1708698

Little D, Muir J (1987) A guide to integrated warm-water aquaculture. Institute of Aquaculture, University of Stirling, Stirling, Scotland, p 238

Maire E, Graham NA, MacNeil MA, Lam VW, Robinson JP, Cheung WW, Hicks CC (2021) Micronutrient supply from global marine fisheries under climate change and overfishing. Curr Biol 31:4132–4138

Martins CIM, Eding EH, Verdegem MC, Heinsbroek LT, Schneider O, Blancheton JP, d'Orbcastel RE, Verreth JAJ (2010) New developments in recirculating aquaculture systems in Europe: a perspective on environmental sustainability. Aquacult Eng 43(3):83–93

Matta G (2015) Effect of water quality on phytoplankton ecology of upper Ganga Canal. Int J Sci Eng Res 6(2):762–768

Mohanty BP, Pati MK, Bhatacharjee S, Hajara A, Sharma AP (2013) Small indigenous fishes and their importance in human health. Adv Fish Res 5:257–278

Napiorkowska-Krzebietke A (2014) Phytoplankton of artificial ecosystems- an attempt to assess water quality. Arch Pol Fish 22:81–96

Parry M, Rosenzweig C, Livermore M (2005) Climate change, global food supply and risk of hunger. Philos Trans R Soc B 360:2125–2138

Porteus CS, Hubbard PC, Uren Webster TM et al (2018) Near-future CO_2 levels impair the olfactory system of a marine fish. Nat Clim Change 8:737–743. https://doi.org/10.1038/s41558-018-0224-8

Prosser CL (1973) Comparative animal physiology, 3rd edn. W.B. Saunders, Philadelphia, p 1011

Ripa J, Olofsson H, Jonzon N (2010) What is bet-hedging, really? Proc R Soc B Biol Sci 277:1153–1154. https://doi.org/10.1098/rspb.2009.2023

Roos N, Islam M, Thilsted SH, Ashrafuddin M, Mursheduzzaman M, Mohsin DM, Shamsuddin ABM (1999) Culture of mola (*Amblypharyngodon mola*) in polyculture with carps—experience from a field trial in Bangladesh. NAGA 22:16–19

Sarkar UK, Lakra WS (2010) Small indigenous freshwater fish species of India: significance, conservation and utilization. Aquacult Asia Mag 15(3):34–35

Sinha A, Gogoi P, Damroy S (2022a) Small indigenous fish (SIF): status and contributions in nutrition and livelihood security of India: a review. Agric Rev. https://doi.org/10.18805/ag.R-2336

Sinha A, Roy A, Gogoi P, Tayung T, Mitesh HM, Mitra A, Mondal S, Das BK (2022b) Exploration of canal resources as a potential source for fish production in the Indian Sundarbans. Aquacult Asia 26(1):3–8

Sogard SM, Berkeley SA, Fisher R (2008) Maternal effects in rockfishes Sebastes spp.: a comparison among species. Mar Ecol Prog Ser 360:227–236. https://doi.org/10.3354/meps07468

Somero GN (1978) Temperature adaptation of enzymes: biological optimization through combined effects of dietary lipids and environmental temperature on growth, metabolism and body composition of channel catfish (*Ictalurus punctatus*). J Nutr 101:1703–1710

Tarplee WH Jr, Louder DE, Weber AJ (1971) Evaluation of the effects of channelization on fish populations in North Carolina's coastal plain streams. Wildlife Resources Commission, Internal Report, Raleigh, NC, p 13

Thilsted SH, Thorne-Lyman A, Webb P, Bogard JR, Subasinghe R, Phillips MJ, Allison EH (2016) Sustaining healthy diets: the role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. Food Policy 61:126–131

Trippel EA, Kjesbu OS, Solemdal P (1997) In: Chambers RC, Trippel EA (eds) Early life history and recruitment in fish populations. Springer, Dordrecht, pp 31–62

Vandeperre F, Methven DA (2007) Do bigger fish arrive and spawn at the spawning grounds before smaller fish: cod (*Gadus morhua*) predation on beach spawning capelin (*Mallotus villosus*) from coastal Newfoundland. Estuar Coast Shelf Sci 71:391–400. https://doi.org/10.1016/j.ecss.2006.07.020

Verdegem MCJ, Bosma RH (2009) Water withdrawal for brackish and inland aquaculture, and options to produce more fish in ponds with present water use. Water Policy 11(S1):52–68

Role of Dietary Supplements in Stress Amelioration of Teleost Fishes

Srijit Chakravarty, Satya Prakash, and Shivendra Kumar

Abstract

In this era of the global scurry for food security, aquaculture has emerged as the leader among the sectors providing a sustainable solution to feed the nine billion people by 2050. However, this challenge of sustainable intensification holds the problem of rising stressors for cultured fish. Being a cold-blooded aquatic vertebrate, feed remains the only input for economically addressing the menace of stress in cultured fishes. The use of aquafeed additives in fish nutrition is a relatively new frontier wherein the focus is mostly on ameliorating attributes other than growth. Probiotics, prebiotics, synbiotics, vitamins, and amino acids are the few most important feed additives being used nowadays for stress amelioration in fish. This chapter focuses on the individual mechanisms and case-to-case studies by authors across the globe to give a holistic view of the use of aquafeed additives for stress amelioration in teleosts.

Keywords

Stress · Feed additives · Probiotics · Prebiotic · Symbiotic · Vitamin · Amino acid

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1 Introduction

Stress mitigation in fish has been a research interest of scientists for a long time. Representing a wide diversity of over 27,000 species (90–95% of which are the most evolutionary advanced group called teleosts), fishes epitomize a variety of habitats, feeding habits, husbandry practices, and stress mitigation measures. Capture fisheries have registered a languor in growth rate since the mid-90s and aquaculture has emerged as the major sector (growing at a rate of 5.3% for the period 2000–2018) in providing fish as the source of 20% protein intake over three billion people of the world (FAO 2020). Marred with wanton intensification, the stocking densities have increased leading to crowding stress and various contaminants in the water sources lead to the development of stress related to heavy metals as well apart from conventional stressors like thermal stress, hypoxia handling stress, etc. With the increased use of high-density fish culture systems like cages, biofloc-based fish cultivation, and the recirculatory aquaculture system (RAS), there is increased dependence on automation and a constant source of electricity failure which will immediately put the cultured stock under immense stress. Changing climates and ocean acidification further lead to thermal stress and pH as well as ionic imbalance stressors which can only be ameliorated by proper dietary additives to help the fishes combat the negative effects on their health. Though the concepts of the ecosystem approach to aquaculture have been in practice nowadays, stress mitigation remains a big constant challenge to aquaculturists and food scientists all over the world (Brugère et al. 2019).

Classically akin to other vertebrates, the stress response in fishes refers to as being primary, i.e., changes in corticosteroid and catecholamine titers in the blood, secondary or changes in digestive enzymes, hydromineral balance, etc., and tertiary, viz. imbalances in growth parameters, behavioral changes stemming from primary or secondary responses (Barton 2002). However, with the advent of molecular diagnostic tools and sublethal sampling techniques, nowadays many immune-reactive genes have been earmarked to be biomarkers for stress like HSP, ACTH, etc. capable of detecting stress at subcellular levels much before they are being reflected by the hormone titers per se.

The outcome of stress in fishes can have both positive (eustress) and negative (distress), depending on the ability of the fish to gain homeostasis, and the duration of the stressor impacting their gross physiological functions (Schreck and Tort 2016). Since the publication of the seminal work on stress by Selye (1950, 1976), stress has been generalized as general adaptive syndrome (GAS) or defined as the "nonspecific response of the body to any demand placed upon it." This definition was later modified by Schreck (2009) as "the physiological cascade of events that occurs when the organism is attempting to resist death or reestablish homeostatic norms in the face of insult." For more definitions given by various other authors see the review by Schreck and Tort (2016). The cascade of events that start with the facing of the stressor is invocation of the neuroendocrine torrent mostly the dopamine or serotonin in teleosts, which is reflected by the titers of catecholamines like adrenaline, noradrenaline, and the corticosteroids like cortisol, respectively.

2 Role of Catecholamines in Stress Response: Synthesis and Effects

Catecholamines (CA) are synthesized, within the chromaffin cell, via the Blaschko pathway beginning with the amino acid precursor tyrosine, however, their release of catecholamines appears to be under complex control (Reid et al. 1998). In face of the stressor, catecholamine release in teleosts follows a bimodal pattern, wherein a burst (5 nm–1000 nM within 1–3 mins) in the initial stages is followed by a sustained release from the chromaffin tissue of the kidney concluding into a de novo synthesis of catecholamines from the interrenal cells (Bonga 1997). Catecholamines generally have a shorter life span in teleosts (~10 mins); however, in the face of acute stress response, they can be in circulation for hours or even days (Randall and Ferry 1992).

Biosynthesis of CA follows two steps, viz. the conversion of tyrosine to L-dihydroxyphenylalanine (L-DOPA) by the action of enzyme tyrosine hydroxylase and the second step where the L-dihydroxyphenylalanine (L-DOPA) to dopamine by the action of L-aromatic amino acid decarboxylase (AADC), the first step being the rate-limiting step in the reaction (Randall and Ferry 1992). Dopamine being the precursor of CAs is transported to the storage granules and hydroxylated to noradrenaline via a copper-containing enzyme, enzyme, dopamine-β-hydroxylase. Following this, noradrenaline is transported from the secretory vesicle, into the cytoplasm, where it is methylated to form adrenaline by the enzyme phenylethanolamine-N-methyltransferase (PNMT). In teleosts, chromaffin cells are the primary storage and release organs of CA in contrast to mammals, in which the CA is released additionally from the flooding of the sympathetic neurons (Reid et al. 1998). In addition to sympathetic nervous stimulation of the chromaffin cells, hypoxia, high doses of K^+ causing nonspecific depolarization of the chromaffin cells, arguably regional acidosis, humoral agents like serotonin, angiotensin, histamine, opioid peptides, natriuretic peptides, CA, and cortisol to some extent modulate the CA release in teleosts (for review see Reid et al. 1998). Increased levels of circulating CA have a profound effect on respiratory and cardiac functions of teleosts via the action of β-adrenergic mechanisms as the teleost heart is under inhibitory cholinergic and stimulatory adrenergic control (Randall and Ferry 1992; Bonga 1997). It also causes increased affinity of hemoglobin for oxygen by stimulating the Na^+/H^+ exchange and shunning the Cl^-/HCO_3^- exchange creating an alkaline erythrocytic microenvironment favoring oxygen binding (Nikinmaa 1992, 2003). It is interesting to note that CA binds to the β-adrenergic receptors of the blood cells and in events of hypoxic stress, the number of such receptors increases profusely (Reid et al. 1991).

3 Effect of Stress on Growth and Reproduction in Fishes

A key factor in stress management is the distribution of metabolic energy away from energy-expensive activities (e.g., growth and reproduction) and activities that require attention to restore homeostasis, such as respiration, dehydration, hydromineral regulation, etc. This reduces the performance of the fish over time (Schreck 2009; Schreck and Bradford 1990). Appetite and food intake are primarily affected in a fish in stress and the major reason for energy deprivation as shown in Brown trout (Pickering and Stewart 1984), Atlantic Salmon (Damsgård et al. 1998), Common carp (Bernier et al. 2012). Recent advancements in this field indicate a strong role of corticotropin-releasing factor (CRF) and other related neuropeptides like urotensin 1 (U1) in the appetite suppression in fishes under stress (Kozicz 2007; Volkoff et al. 2005). Furthermore, there are reports of acute hyperglycemia in face of stress which is positively correlated with metabolic rate as seen in *Colisa fasciata* (Chaudhry and Nath 1985; Conde-Sieira et al. 2018). Blood glucose has been used as a reliable biomarker in stress-induced due to exposure to heavy metals in fish (Javed et al. 2017). 8–16% suppression in growth rate was correlated with a 20% increase in the respiration rate in coho salmon (Vaughan et al. 1982). Endocrinologically, growth suppression in face of stress may be attributed to the action of CAs stimulating energy consumption, gluconeogenesis, and lipolysis (Bonga 1997).

It is quite paradoxical that stress and reproduction, both crucial for the existence of any species aim at striking a balance for attaining homeostasis in the face of challenges thrown towards the existential crisis faced by the individual. Reduction in reproductive success is a commonly noted phenomenon in teleosts; however, contrary reports do exist where stress facilitates reproduction (Rousseau et al. 2021). Stress primarily alters the levels and patterns of reproductive hormones that influence maturation in fishes (mostly captive) by activation of the hypothalamic–pituitary–interrenal (HPI) axis in conjunction with the rise and fall of glucocorticoid (GC) titers in the blood (Barton 2002; Barton and Iwama 1991; Cook et al. 2011). Recent interest has emerged in correlative studies linking the GC titers with measures of the reproductive fitness of an individual within a population. The "Cort-Fitness hypothesis" has been proposed wherein elevated pre-stress cortisol levels are assumed to indicate an individual or population of reduced relative fitness however such models have not found overwhelming support in the fish species tested so far (Bonier et al. 2009).

There is a mixed school of thought on whether cortisol inhibits reproduction or not. Foo and Lam (1993a, b) have shown that cortisol if administered externally leads to a reversed oocyte growth, serum testosterone, and 17β-estradiol in Nile tilapia, *Oreochromis mossambicus*. On contrary, Pankhurst and Van Der Kraak (1995) have shown that cortisol administration does not affect testosterone and 17β-estradiol production, at least at the level of ovarian steroidogenesis in goldfish, *Carassius auratus*, carp, *Cyprinus carpio*, and sparid, *Pagrus auratus*. The adverse effects of stress on reproduction on *Acanthochromis polyacanthus*, too, appear to have been caused by higher levels than those of ovarian steroidogenesis (Pankhurst 2011). There is no concluding evidence that stress-mediated reproductive failure is not linked with cortisol-mediated GTH blockade, as shown in Rainbow Trout *Oncorhynchus mykiss*, by Pankhurst and Van Der Kraak (2000) indicating the involvement of a separate pathway other than the cortisol-mediated impairment of maturation and steroidogenesis or stress on the reproductive physiology of fishes.

Arginine vasotocin appears to be an important component of stress response to fish that can affect reproduction by playing a regulatory role in ACTH secretion (Balment et al. 2006). Urotensin-I is also a corticotropic, probably higher than CRF-I, and is involved in the regulation of cortisol during spawning as shown in Masu salmon, *Oncorhynchus masou* (Westring et al. 2008).

It is pretty interesting to note that the social environment of fish can also affect reproduction via the interaction with the endocrine stress response. Leitz (1987) reported that, in Male Siamese Fighter fish, *Betta splendens*., social factors (like isolation or community rearing) have a conspicuous control over the gonadal steroid metabolism. Males grown in isolation had longer fins and their testes produced more 11-oxy- and more 5β-steroids than those of the males reared in community housing structure (social stressor). In African cichlid *Astatotilapia burtoni,* it is emphasized that social cohesion leads to increased cortisol circulation levels and cortisol is higher in ascending males compared to socially stable males (Huffman et al. 2015; Maruska and Fernald 2015). Fox et al. (1997) reported that the reproductive capacity of fish is also affected by similar social interactions because the size of GnRH neurons in the hypothalamic-preoptic area and the testicular dimensions correlate inconsistently with the social environment. They further concluded that the level of the stress hormone cortisol depends critically on both the social and reproductive status of an individual fish and the stability of its social situation.

4 Stress and Nutrition in Fishes

Under intensive cultural conditions, fishes are exposed to bimodal attacks from natural stressors (water quality and hypoxia) and deteriorating health conditions (parasites and infectious diseases). As a whole these exert negative impacts on fish welfare and overall performance, translating to subsequent economic losses. Although good management practices contribute to reducing the effects of stress, crowding has an immense impact on the stress experienced by fish in general. Balanced food and sound nutritional status is important to avoid symptoms of deficiency, maintain adequate animal function, and maintain the normalcy of health. In addition, feed fortification in terms of certain nutrients [amino acids, essential fatty acids (FAs), vitamins, or minerals] can significantly improve health status and disease resistance in fishes. Ingredients are there and tested for their antioxidant power, as fish may be at risk of peroxidative attacks due to a large number of unsaturated FAs in both fish tissue and diet (Hoseinifar et al. 2020). Functional elements other than essential nutrients (e.g. probiotics, prebiotics, and immunostimulants) are currently being considered in fish diets and aim to improve fish growth and/or nutrition, health status, stress tolerance, and resistance to diseases (Oliva-Teles 2012). Such formulations are becoming more and more popular in substituting the use of antibiotics in aquafarms, which not only have an adverse impact on the environment but can bioaccumulate in the tissues as well as promote antimicrobial resistance (Kümmerer 2009). Feed, among other things, thus has a profound effect on stress tolerance and health, so, to grow sufficiently and cope with stress and disease, fish must be fed with nutritionally balanced as well as fortified feed to meet all of their physiological needs (Trichet 2010).

4.1 Types of Dietary Additives in Stress Amelioration

Over the past few decades, the driven growth in demand for cultured fish as a protein source has increased dramatically due to the development and adoption of cutting-edge technologies, climate-smart aquaculture techniques, and nutrient-dense feed (Gupta et al. 2021; Hu et al. 2020). This growth, however, has proved to be a testament to the various environmental and agricultural pressures that pose significant challenges to the aquaculture sector. Stressful farming conditions damage the health of fish leading to economic loss in terms of slow growth and disease prevalence. Therefore, increasing the resilience of cultivated species is very important in ensuring the sustainable development of the aquaculture sector (Ciji and Akhtar 2021). Among the various mitigation strategies, dietary interventions appear to need the hour strategy to improve physical stability and resistance to fish in face of continuously multiplying stressors. By definition, dietary additives are categorized as non-nutritive products that affect the utilization of the feed or the productive performance of the animal. Based on the type of additive and their intent of usage they may be grouped under various sub-categories as influencing feed stability, feed manufacturing, and physical properties of aquafeed (antifungals, antioxidants, and pellet binders), modifying fish growth, feed efficiency, metabolism, and performance (free fatty acids, digestion modifiers, enzymes, prebiotics, probiotics), etc., modify animal health (drugs and immunostimulants), modify consumer acceptance (viz. carotenoids, xanthophylls, etc.).

4.2 Probiotics

With increasing concerns over the bioaccumulation of therapeutic chemicals in fishes and aquatic food supplies, probiotics have gained a niche in the arena of prophylactic inputs used to combat diseases by using the beneficial microbiota of soil and water to ward off harmful ones. Pro; for and Bios; Life, probiotics translates to the use of “for Life” of living microorganisms which colonize the gut microbiota of a healthy fish as well its environment, thereby creating an ecosystem that is conducive for optimal growth (Sahu et al. 2008). Though the use of gut probiotics has gained the maximum momentum in research promoting feed digestibility and translating to a healthier translation in terms of muscle growth, creating a conducive environment in terms of soil and water is slowly emerging as an alternative to a chemical-free culture environment for fishes. The advent of bacterial genera like *Bacillus* spp. and some other species including *Aerobacter* sp., *Nitrobacter* sp., and *Saccharomyces cerevisiae* (yeast) has done a remarkable task in the water quality improvement (Jahangiri and Esteban 2018; Nahid Akter et al. 2016). Extensive reviews on probiotic supplementation in the aquaculture industry are published by

Martínez Cruz et al. (2012), Zhou et al. (2012), Mohapatra et al. (2013), Zorriehzahra et al. (2016), Dawood et al. (2019), Adel and Dawood (2021), and El-Saadony et al. (2021).

Aeromonas hydrophila is the normal constituent of the gut microflora of fish (Kumar et al. 2006; Sivasubramanian et al. 2012) that is present in freshwater, aquatic plants, and fish, which exhibit hemotoxic responses to the mucus of freshwater fish. Aeromonas *hydrophila* is considered an etiological agent of more than a few diseases of carp and catfishes including hemorrhagic septicemia, characterized by the presence of abdominal distension, ulcers, small superficial lesions, abscesses, exophthalmia, and local hemorrhages, particularly in the gills and opercula (Sahoo et al. 2011). In a study conducted by Irianto and Austin (2003), it was shown that formalin-inactivated cells of *Aeromonas hydrophila* A3–51 when applied as a feed additive show a beneficial effect in controlling infection by atypical *A. salmonicida* in goldfish. Research on autochthonous probiotic strains isolated from the gut of *Labeo rohita* has shown that cellular components (cell wall proteins) and live cells of probiotics *Bacillus licheniformis* and *Bacillus pumilus* can potentially be used as adjuvant or vaccine against *Aeromonas* sp. infection and can act as a substitute to antibiotics in aquaculture (Ramesh et al. 2015). The cell wall isolates and subcellular fractions withstand a temperature up to 90 ° C and a pH range of 3.0–10.0 making them ideal candidates to withstand gut pH when administered orally (Giri et al. 2011). Gobi et al. (2018) reported that *Bacillus licheniformis* strain Dahb1 improves growth performance, mucus, and serum immune parameters, antioxidant enzyme activity as well as resistance against *Aeromonas hydrophila* in tilapia *Oreochromis mossambicus.* In Grass Carp, a probiotic strain of *Bacillus subtilis* can protect against oxidative stress damage induced by *Aeromonas hydrophila* (Tang et al. 2019). The authors noted that within 42 days of trial, the probiotic reduced level of oxidative stress with a decrease in the level of MDA, increased antioxidant defenses, including an increase in total antioxidant capacity (T-AOC), increased activities of SOD and CAT, increased levels of GSH, and upregulated gene expression of antioxidant enzymes (SOD, CAT, and Gpx); and improved immune response with the level of anti-inflammatory cytokines IL-10 messenger RNA (mRNA) being upregulated and the levels of proinflammatory cytokines TNF-α, IL-1β, and IL-8 mRNA being downregulated. Probiotic *Enterococcus faecium*, a marine bacterium administered to the diet of olive flounder (*Paralichthys olivaceus*) infected with the marine fish pathogen *Lactococcus garvieae,* causing Lactococcosis, showed enhanced lysozyme and complement activities between 9 and 15 and 9 and 13 days, respectively, and antiprotease after 5 days of probiotic treatment including upregulation of TNF-α and IL-1β expressions in kidney and spleen (Kim et al. 2012). Dietary administration of *Zooshikella* sp. (strain JE 34) enhances the innate immune response and disease resistance of *Paralichthys olivaceus* against *Streptococcus iniae* (Kim et al. 2010). The authors noted that the immune parameters in the treated groups enhanced significantly after the eighth week; the weight gain significantly increased after the fourth week of treatment with enriched diets.

There is a very conspicuous relationship between water deterioration and its physiological consequences in live fish transport. Fishes experience heavy handling stress due to deteriorating water quality and thereby keeping conducive water quality parameters is paramount in fish culture and transport. The main issue in short transports (<8 h) is the prevention of water pH reduction, while in long transports (>8 h) it is the increase in ammonia. Plasma cortisol is the most employed marker for stress and is acutely elevated upon short episodes of transport, but remains elevated even in long-transport events. Plasma glucose is considered to be a good marker for handling stress (Sampaio and Freire 2016). Sole (Solea senegalensis) subjected to bacterial infection and handling stress after probiotic treatment with autochthonous bacteria (*Shewanella hafniensis* and *Enterococcus raffinos*e) showed a better response in mitigating stress induced by handling and transport of (Peixoto et al. 2018). *Shewanella putrefaciens*, also known as Pdp11, isolated from the skin of healthy gilthead seabream provides resistance to handling stress by upregulating the mucosal immune system (Cordero et al. 2016). In a closed recirculatory system, probiotics supplied in the rearing water and the diet of fish enhanced the stress tolerance and the nonspecific immune system of Japanese flounder (*Paralichthys olivaceus*), providing them a higher resistance against stress conditions and pathogens (Taoka et al. 2006). The authors noted that probiotic supplementation improved the water quality parameters, in terms of pH, $NH_4 - N$, $NO_2 - N$, and $PO_4 - P$ in a closed recirculatory system.

4.3 Prebiotics

Prebiotics are defined as “selectively fermented ingredient non-digestible food ingredient that beneficially affects the host by selectively stimulating the growth and/or the activity of one or a limited number of bacteria in the colon” (Ringø et al. 2010; Gibson et al. 2010). The concept was introduced by Gibson and Roberfroid in 1995 with a slightly alternative approach which consists of regulation of the gut microbiota (Gibson and Roberfroid 1995). Prebiotics has several advantages, but the main advantage of prebiotics over probiotics is that they are natural feed ingredients. Their incorporation into the diet does not require particular precautions and their authorization as feed additives may be more easily obtained, despite some concerns about their safety and efficacy (Yousefian and Amiri 2009). Prebiotics are non-digestible carbohydrates that can be classified according to molecular size or degree of polymerization (number of monosaccharide units) such as monosaccharides, polysaccharides, or oligosaccharides used for optimal bowel function for preferring the proliferation of normal bacterial flora and prevent the ontogenesis of pathogens (Roberfroid 2001, Akhter et al. 2015). Prebiotics are used as energy sources for gut bacteria and can be referred to as functional saccharides (Ibrahim 2018). The most commonly used prebiotics in aquaculture is starch, inulin, fructooligosaccharide (FOS), mannan oligosaccharide (MOS), etc. However, some authors do not consider mannan oligosaccharides as prebiotics sensu stricto, because they do not alter the intestinal microbiota, even though they can improve performance in a variety of animal species, including weaned piglets and rabbits (Bovera et al. 2012). The usual target for prebiotics is the two lactic acid bacterial genera, *Bifidobacterium* and *Lactobacillus*. The enhancement of the growth of these bacterial species also results in the production of bacteriocins, which help prevent the growth of pathogenic bacteria (Biswas et al. 2021). The mechanism of action of prebiotics is multifaceted, viz. increasing glucose uptake (Breves et al. 2001) and bioavailability of trace elements (Bongers and van den Heuvel 2003). These trace elements help in gut acidification and thereby prevent microbial colonization.

Research on prebiotics gained momentum to find alternatives for antimicrobial growth promoters (AGP) in the poultry industry following its ban in Europe in 2006 (Teirlynck et al. 2011). Since then, FOS and MOS at 0.25–0.5% are being incorporated in broiler diets and are giving similar results to AGPs (Emami et al. 2012). In an initial study by Wang and Wang (1997) inulin was administered via intraperitoneal injection into grass carp (*Ctenopharyngodon idellus*) and tilapia (*Tilapia aureus*) but the results were not significantly different control group. The first in vitro trials with prebiotics in fishes started in 2006 (Gatlin et al. 2006) with fructooligosaccharide (FOS) which at a concentration of 0.375% significantly alters the microbial population of red drum (*Sciaenops ocellatus*). In addition to natural inulin, insoluble inulin (γ-inulin) has been suggested to possess adjuvant activity because it activates the alternative complement pathway (Silva et al. 2004).

Inulin is one of the basic prebiotics used in aquaculture. Not all species need to have beneficial effects on the gastrointestinal microbiome following inulin supplementation. There have been various reports related to dietary inclusion rates of inulin on different fish species summarized in Table 1. From the above table, it is clear that inulin supplementation is species-specific and the higher doses (above 2% or 20 g/kg feed) are detrimental to the gut-associated microbiota.

FOS (fructooligosaccharide) is yet another commonly used prebiotic in aquaculture (Soleimani et al. 2012). FOS is the common name for fructose oligomers, chemically composed mainly of chains of fructose units with a terminal glucose molecule unit linked by glycosidic bridges β-(2–1) (Sabater-Molina et al. 2009; Flores-Maltos et al. 2016). These are reserve carbohydrates present in many plants and vegetables such as Jerusalem artichoke, asparagus, chicory, wheat, tomatoes, banana, etc. (Mussatto, 2009). Native inulin is processed and transformed into FOS or short-chain fructans (scFOS) with a degree of polymerization between 2 and 10 (generally 5) as a result of partial enzymatic hydrolysis with inulinase (Gibson and Rastall 2006). Various studies pertinent to the use of FOS in the stress amelioration of teleost fishes are summarized in Table 2.

Mannan oligosaccharides (MOS) are glucomannoprotein complexes derived from the cell wall of yeast (*Saccharomyces cerevisiae*). MOS molecules induce intracellular signaling that may increase the production of proinflammatory cytokines which have beneficial features as feed additives to teleost fish. Galactomannan is purified from various plants' endosperm as coconut and gum, meanwhile, glucomannan can be obtained from konjac and orchid species. One of the popular uses of heteromannans in the food industry is their routine use as gelling, thickening, or stabilizing agents (Nopvichai et al. 2019). It has been shown that in addition to enhancement of growth and survival, MOS increased innate immune and also increased microvilli density and length in the intestine of European sea bass and

Table 1 Dietary inclusion rates on Inulin were tested on various species along with the effect on gut-associated microbiota and performance

Sl. no.	The inclusion rate of Inulin (%)	Species	Effect on intestinal function, growth, and immune response	References
1	15	Arctic charr (*Salvelinus alpinus*)	Intestinal damage	Olsen et al. (2001) and Ringø et al. (2006)
2	7.5	Atlantic salmon (*Salmo salar* L.)	Stimulated intestinal growth, but did not affect the nutrient hydrolytic and absorptive capacity	Refstie et al. (2006)
3	7.5	Atlantic salmon (*Salmo salar* L.)	Reduced the diversity of gut microbiota in terms of Pseudoalteromonas and Micrococcus spp.	Bakke-McKellep et al. (2007)
4	0.5–1 (5 or 10 g inulin/kg)	Seabream (*Sparus aurata* L.)	Significant inhibition in phagocytosis and respiratory burst by leucocytes and inulin does not seem to be an optimal prebiotic for seabream	Cerezuela et al. (2008)
5	2	Siberian sturgeon (*Acipenser baeri*)	No significant differences in total short-chain fatty acid (SCFA) and lactate content and increased gas production	Mahious et al. (2006a)
6	1–3	Beluga Sturgeon (*Huso huso*)	Lower weight gain (WG), specific growth rate (SGR), protein efficiency ratio (PER), energy retention (ER), feed efficiency (FE), and protein retention (PR) in treated groups. Inulin is not appropriate for supplementation in the diet of beluga	Reza et al. (2009)
7	2	Turbot (*Psetta maxima*)	Growth and bacterial community in the gut (Bacillus and Vibrio sp.) were not affected. The final mean weight of the treated group was significantly higher	Mahious et al. (2006b)
8	0.5	Nile tilapia (*Oreochromis niloticus*)	Increased hematocrit and NBT activity levels, and lysozyme activity	Ibrahem et al. (2010)
9	0.5	Hybrid Surubim (*Pseudoplatystoma* sp)	Increased erythrocytes and reduced circulating neutrophils were observed in this group No differences in blood glucose, serum protein, or lysozyme levels	Mouriño et al. (2012)
10	0.5–1	Rainbow trout (*Oncorhynchus mykiss*)	Significant improvement in weight gain and intestinal absorption of Ca^{2+}	Ortiz et al. (2013)

(continued)

Table 1 (continued)

Sl. no.	The inclusion rate of Inulin (%)	Species	Effect on intestinal function, growth, and immune response	References
11	0.5–1	Common carp (*Cyprinus carpio*)	Dietary inulin had no significant effects on digestive lipase, protease and amylase activities	Eshaghzadeh et al. (2015).
12	0.5	Nile tilapia (*Oreochromis niloticus*)	Fingerlings had better growth performance and survival rates	Tiengtam et al. (2017)
13	0.4	Nile tilapia (*Oreochromis niloticus*)	Alleviation of salinity-induced stress at 16 PSU	Zhou et al. (2020)
14	0.2	Common carp (*Cyprinus carpio*)	Improvements in serum immune parameters, lysozyme (LYZ), alternative complement (ACH50), total immunoglobulin (total Ig), and myeloperoxidase (MPO)	Ajdari et al. (2022)
15	0.5–1	Pacu (*Piaractus mesopotamicus*)	Supplementation for 15 days minimized the stress response and increased the innate immune responses	de Campos et al. (2022)

gilthead seabream, respectively (Merrifield et al. 2010; Torrecillas et al. 2012). Furthermore, MOS has functional groups that can bind radicals. Therefore, MOS is considered an excellent natural antioxidant and is widely used in human and animal health (Lu et al. 2022). The summary findings of MOS supplementation rates and their respective effect on stress amelioration and gut health are summarized in Table 3.

4.4 Synbiotics

Synbiotics, as the name, suggests amalgamating the beneficial effects of both pre and probiotics so that they act synergistically towards the benefit of the host gut microbiota. Sensu stricto, a product containing oligofructose and probiotic bifidobacteria would fulfill the definition, whereas a product containing oligofructose and a probiotic *Lactobacillus casei* strain would not. Thus the prebiotic used in the combination should be utilizable by the probiont; otherwise, it cannot be accredited the status of a symbiotic. In the case of synergism, it is said to occur when the combined effect of the two products is significantly greater than the sum of the effects of each agent administered alone.

In aquaculture, studies on synbiotic feed additives are relatively newer and the research is still in its infancy compared to animal husbandry and dairying. The first application of synbiotics in fish is that of Rodriguez-Estrada et al. (2009). In this study, a commercial preparation of *E. faecalis*, and two kinds of ingredients, mannan

Table 2 Dietary inclusion rates on fructooligosaccharide (FOS) were tested on various species along with the effect on gut-associated microbiota and performance

Sl. no.	The inclusion rate of FOS (%)	Species	Effect on intestinal function, growth, and immune response	References
1	0.2–0.4	Yellow croaker (*Larimichthys crocea*)	Dietary supplementation of FOS at a dose of 0.4% improved growth, feed efficiency ratio, nonspecific immune responses, and disease resistance	Ai et al. (2011)
2	1–3	Caspian roach (*Rutilus rutilus*)	FOS significantly increases Caspian roach fry resistance to salinity stress	Soleimani et al. (2012)
3	1–2	Stellate sturgeon (*Acipenser stellatus*)	Dietary FOS at 1% is optimum and it stimulated the lysozyme activity and white blood cell count of stellate sturgeon	Akrami et al. (2013)
4	0.2–0.4	Ovate pompano, (*Trachinotus ovatus*)	FOS had a significant interaction with enhancing the immune responses and disease resistance of juvenile ovate pompano	Zhang et al. (2014a)
5	0.4–0.8	Blunt snout bream (*Megalobrama amblycephala*)	Improve the growth, immune response, and antioxidant capability of fish, as might consequently lead to enhanced disease resistance at a 0.8% level	Zhang et al. (2014b)
6	0.4–0.8	Blunt snout bream (*Megalobrama amblycephala*)	Supplementation of 0.4% FOS could increase the nonspecific immunity, antioxidant capacity, and HSP70 and HSP90 expression of blunt snout bream and enhance its resistance to high ammonia stress	Zhang et al. (2015)
7	1–2	Rohu (*Labeo rohita*)	Improves immune status and allows better protection under sub-lethal nitrite stress	Singh et al. (2015)
8	1	Rohu (*Labeo rohita*)	Allows better survival and immunity under low pH-induced stress	Singh et al. (2019)
9	0.4–0.8	Goldfish (*Carassius auratus*)	FOS attenuated triphenyl tin (TPT)-induced oxidative stress in goldfish by partly preventing alterations in the activities of antioxidant enzymes and the expression of antioxidant- and ROS scavenger-related genes	Zhang et al. (2021)
10	1–2	Rohu (*Labeo rohita*)	Antioxidant capacity when challenged to sub-lethal nitrite stress was improved in prebiotic (1% FOS) fed groups. A higher level of FOS at 2% imposes a negative impact on serum biochemical parameters and digestive enzyme activity	Singh et al. (2021)

Table 3 Dietary inclusion rates on mannanoligosaccharide (MOS) were tested on various species along with the effect on gut-associated microbiota and performance

The inclusion rate of MOS (%)	Species	Effect on intestinal function, growth, and immune response	References
0.2–0.4	Pacu (*Piaractus mesopotamicus*)	Minimized stress response and enhanced innate immunity	Soares et al. (2018)
0.4	Gilthead seabream (*Sparus aurata*)	Diet supplemented with MOS has positive effects on the survival rate and the fatty acids profile	Gelibolu et al. (2018)
0.4	Caspian trout (*Salmo trutta caspius*)	The activity of lysozyme, immunoglobulin M, and alternative complement increased	Jami et al. (2019)
0.6	Hybrid grouper (*Epinephelus lanceolatus*♂ × *Epinephelus fuscoguttatus*♀)	Supplementation did not improve growth performance or feed utilization however, enhanced immune-related gene expression in the intestine and liver	Ren et al. (2020)
0.5	European sea bass (*Dicentrarchus labrax*)	Serum cortisol was significantly decreased in fish exposed to confinement challenges	Serradell et al. (2020)
0.1	Rainbow trout (*Oncorhynchus mykiss*)	Enhance immunity and improve rainbow trout resistance	Khodadadi et al. (2021)
0.5–1	Thinlip Grey mullet (*Liza ramada*)	Marked improvements in growth performance, digestive enzyme activity, blood chemistry, and antioxidative capacity	Magouz et al. (2021)
0.4	Gilthead Sea bream (*Sparus aurata*)	Enhance the immune health (upregulation of innate immune genes) status of the gilthead seabream during thermal stress	Khosravi-Katuli et al. (2021)
0.4	Asian catfish (*Clarias batrachus*)	Significantly improved ($P < 0.05$) specific growth rates, protein efficiency ratio, and survival rate	Ciji and Akhtar (2021)
0.4	Grass carp (*Ctenopharyngodon idella*)	MOS supplementation could protect intestinal ultrastructure, reduce intestinal mucosal permeability and maintain intestinal structural integrity via inhibiting MLCK and RhoA/ROCK signaling pathways	Lu et al. (2022)

oligosaccharide (MOS) and PHB (poly hydroxy butyrate, a prebiotic included in the group of biopolymers) used as probiotics and prebiotics, respectively, were fed to juvenile rainbow trout (13.2 ± 0.25 g) for 12 weeks. The study showed that *E. faecalis* improved the immunological parameters such as hematocrit value, phagocytic index and activity, and mucus production when administrated alone or combined with mannan oligosaccharides. It is noteworthy that the phagocytic activity was 57.6% and the hematocrit value was 54.3% higher than the control group. When challenged with *Vibrio anguillarium* the synbiotic-fed group (EM and EMP, respectively) showed better performance and recorded significantly lower mortalities over the control group. The authors opine that symbiotic application improved absorption conditions, due to which *E. faecalis* could affect IECs to secrete an array of cytokines that modulate the functions of dendritic cells (DCs), T cells, and B cells in the gut-associated lymphoid tissue.

A study by Ye et al. (2011) involved the diets of Japanese flounder *Paralichthys olivaceus* supplemented with FOS, MOS and *Bacillus clausii* isolated from grouper (*Epinephelus coioides*) intestine, alone or in combination. Fishes held in cages and fed a diet having the combination of FOS, MOS, and *B. clausii* had the highest weight gain rate (WGR) and they recorded the highest lysozyme activity showing improved stress tolerance and disease resistance in the fed fishes. The authors concluded that the diets supplemented with FOS, MOS, and *B. clausii* improved growth performance and health benefits of the Japanese flounder more than other diets or the control diet.

Hoseinifar et al. (2015) investigated the effects of dietary supplements of galactooligosaccharides (GOS), *Pediococcus acidilactici*, and *P. acidilactici* þ GOS on innate immune response, skin mucus as well as disease resistance of rainbow trout (*Oncorhynchus mykiss*) fingerlings (15.04 ± 0.52 g). The results indicated that the three supplemented diets significantly increased innate immune response and skin mucus parameters in rainbow trout. The highest innate immune response, skin mucus activity, as well as protein level, were observed in synbiotic-fed fish. Furthermore, at the end of the feeding experiment, some fish were intraperitoneally injected with *Streptococcus iniae* to determine the disease resistance. The mortality of fingerlings fed supplemented diet was significantly lower than fish from the control group being the lowest mortality recorded in the synbiotic-fed fish group.

Studies by Kumar et al. (2018) revealed the beneficial effects of the combined supplementation of *Bacillus subtilis* and MOS as synbiotics on growth performance, body composition, digestive enzyme activity, and intestinal microbiota of *Cirrhinus mrigala* fingerlings. The authors noted that the combination of high probiotic (150 × 107 CFU/mL/kg feed) and high prebiotic (6 g/kg feed) is best suited for *C. mrigala* fingerlings for optimum production.

Dawood et al. (2020) noted significant ($P < 0.05$) elevation in villi length by dietary supplementation of symbiotic (*Aspergillus oryzae* and β-glucan) over the other feeding regimes for Nile tilapia (*Oreochromis niloticus*). Further, synbiotic additives effectively elevated the activity of antioxidative enzymes (SOD and CAT) as well as enhanced NBT, IgM, lysozyme, bactericidal, and phagocytosis which indicated improved immunity of tilapia by synbiotic additives.

4.5 Vitamins

Vitamins, specifically vitamin C and E have gained momentum in research pertinent to fish welfare in aquaculture especially due to stress mitigation and antioxidant properties. A requirement of vitamin C in fish was demonstrated for the first time in 1965 (Kitamura 1965). In 1961 rainbow trout with deformed vertebrae (scoliosis and lordosis) were found in many fish ponds in Japan. The fish had mainly been fed artificial dry diets, and the observations initiated experimental studies by Kitamura (1965), showing for the first time a specific requirement for ascorbic acid (AA) in fish. Since then a substantial increase in intensive aquaculture production has taken place, and with concomitant increased efforts to investigate the various aspects of vitamin C in fish nutrition (Sandnes 1991). Unlike the B vitamins, AA has no coenzyme function but acts as a cofactor in various hydroxylation reactions in living tissues, of which the hydroxylations of collagen proline and lysine in connective tissues have been mainly studied. Ascorbic acid (AA) is further regarded as an important general modulator of redox systems in the body. In the body, AA interacts with the metabolism of catecholamines and corticosteroids. It is required for the biosynthesis of noradrenaline from dopamine where AA acts as a co-substrate for the enzyme B-monooxygenase (Robinson et al. 1985). It also affects the metabolism of corticosteroids as demonstrated experimentally by the application of exogenous ACTH resulting in changes in AA levels of the body similar to those occurring in states of stress.

It is known that animals neither biosynthesize tocopherols nor store them in large amounts in their bodies (Trushenski and Kohler 2007). Low levels of vitamin E in the diet depleted alternative complement pathway activity and also nonspecific haemagglutination. Also, fish fed a non-supplemented diet showed an elevation of plasma cortisol basal levels without a stressor influence. Low levels of vitamin E in the diet also produced an increase in erythrocyte fragility (Montero et al. 2001). Detailed reports on the effect of vitamin E on farmed fishes are available in the review by El-Sayed and Izquierdo (2022).

4.6 Amino Acids

Protein is the most expensive part of fish diets and supplies amino acids (AA) for energy, growth, protein synthesis and as substrates for key metabolic pathways. Functional AA is a term used to describe AA that is involved in cellular processes apart from protein synthesis. A deficiency, or imbalance, in functional AA, may impair body metabolism and homeostasis. Recent years have seen an increased interest in AA to increase disease resistance, immune response, reproduction, behavior, and more. This has led to a boost of commercially available functional fish feeds that aim to optimize fish performance and quality of the product.

Arginine: In vivo and in vitro experiments in channel catfish confirmed this positive effect on the immune system, as arginine supplementation improved macrophage killing and phagocytosis abilities. Moreover, arginine increased hematocrit, hemoglobin, erythrocyte count, and lysozyme activity, as well as enhanced native T cells and B-lymphocytes proliferation after mitogenic exposure.

Glutamine: Plays a crucial role in the intestinal health of fish, by modulating intestinal structure, protecting against oxidative damage, and acting as an energy substrate for the enterocytes. Glutamine supplementation increased growth and intestinal structure in red drum (*Sciaenops ocellatus*). Furthermore, glutamine plays a key role in nitrogen detoxification, as the enzyme glutamine synthase binds ammonia to glutamate forming glutamine.

Tryptophan: Tryptophan is the precursor for the neurotransmitter serotonin (5-hydroxytryptamine, 5-HT). Supplementing dietary tryptophan has been shown to reduce aggressive behavior in Atlantic cod and fighting fish (*Betta splendens*), through the calmative effects of 5-HT (Höglund et al. 2005; Clotfelter et al. 2007). Dietary tryptophan may alleviate stress, as dietary tryptophan attenuated stress-induced anorexia in brown trout (*Salmo trutta*) (Höglund et al. 2007) and counteracted stress-induced increase of plasma cortisol in rainbow trout (Lepage et al. 2002).

Methionine: Methionine is an essential amino acid (EAA) and can be used to synthesize cysteine, which together with methionine constitutes the sulfur AA (SAA). Methionine is the most common methyl donor in the body, in addition to participating in protein synthesis. Methionine-derived metabolites such as taurine and glutathione function as antioxidants within the body. In mammals, taurine and glutathione, have a significant impact on oxidative and inflammatory status. Taurine and especially its halides reduced proinflammatory cytokines and interleukins in adipose tissues (Marcinkiewicz and Kontny 2014) and as such can modulate the inflammatory response. Taurine depletion may induce oxidative and inflammatory stress, which is closely associated with metabolic syndrome and may reduce cell viability (Espe and Holen 2013).

5 Conclusion

Stress in fish has been an interesting research topic in light of the recent findings among fish nutritionists in search of a sustainable future of aqua farming as the stressor-free environment can harness the actual genetic gain achievable for the fish growth. There have been numerous studies on aquafeed additives that can ameliorate the stress in fish and more importantly do not hamper the cascade of other production factors most importantly the taste and flavor of the fish by bio-accumulating in the fish muscle. The first choice among the fish nutritionists is probionts of the gut and associated microflora and the second is by selectively enriching the probiotic microflora using the complex oligosaccharides which could be used as feed by the probionts or the prebiotic inclusions. Synbiotics are a relatively newer genre of feed additives being used nowadays for growth supplementation and augmenting the innate immune response. Vitamins and amino acids are also novel areas warranting further research as they offer huge scope being included in precision diets aimed at specific age groups in fish production.

References

Adel M, Dawood MA (2021) Probiotics application: implications for sustainable aquaculture. In: Probiotic bacteria and postbiotic metabolites: role in animal and human health, pp 191–219. https://doi.org/10.1007/978-981-16-0223-8_8

Ai Q, Xu H, Mai K, Xu W, Wang J, Zhang W (2011) Effects of dietary supplementation of Bacillus subtilis and fructooligosaccharide on growth performance, survival, non-specific immune response and disease resistance of juvenile large yellow croaker, Larimichthys crocea. Aquaculture 317(1–4):155–161

Ajdari A, Ghafarifarsani H, Hoseinifar SH, Javahery S, Narimanizad F, Gatphayak K, Van Doan H (2022) Effects of dietary supplementation of PrimaLac, Inulin, and Biomin Imbo on growth performance, antioxidant, and innate immune responses of common carp (Cyprinus carpio). Aquac Nutr 2022

Akhter N, Wu B, Memon AM, Mohsin M (2015) Probiotics and prebiotics associated with aquaculture: a review. Fish Shellfish Immunol 45(2):733–741

Akrami R, Iri Y, Rostami HK, Mansour MR (2013) Effect of dietary supplementation of fructooligosaccharide (FOS) on growth performance, survival, lactobacillus bacterial population and hemato-immunological parameters of stellate sturgeon (Acipenser stellatus) juvenile. Fish Shellfish Immunol 35(4):1235–1239

Bakke-McKellep AM, Penn MH, Salas PM, Refstie S, Sperstad S, Landsverk T et al (2007) Effects of dietary soyabean meal, inulin and oxytetracycline on intestinal microbiota and epithelial cell stress, apoptosis and proliferation in the teleost Atlantic salmon (Salmo salar L.). Br J Nutr 97 (4):699–713

Balment RJ, Lu W, Weybourne E, Warne JM (2006) Arginine vasotocin a key hormone in fish physiology and behavior: a review with insights from mammalian models. Gen Comp Endocrinol 147:9–16. https://doi.org/10.1016/j.ygcen.2005.12.022

Barton BA (2002) Stress in fishes: a diversity of responses with particular reference to changes in circulating corticosteroids. Integr Comp Biol 42(3):517–525. https://doi.org/10.1093/ICB/42.3.517

Barton BA, Iwama GK (1991) Physiological changes in fish from stress in aquaculture with emphasis on the response and effects of corticosteroids. Annu Rev Fish Dis 1(C):3–26. https://doi.org/10.1016/0959-8030(91)90019-G

Bernier NJ, Gorissen M, Flik G (2012) Differential effects of chronic hypoxia and feed restriction on the expression of leptin and its receptor, food intake regulation, and the endocrine stress response in common carp. J Exp Biol 215(13):2273–2282. https://doi.org/10.1242/jeb.066183

Biswas A, Mohan N, Dev K, Mir NA, Tiwari AK (2021) Effect of dietary mannan oligosaccharides and fructo-oligosaccharides on physico-chemical indices, antioxidant and oxidative stability of broiler chicken meat. Sci Rep 11(1):1–9

Bonga SEW (1997) The stress response in fish. Physiol Rev 77(3):591–625. https://doi.org/10.1152/Physrev.1997.77.3.591

Bongers A, van den Heuvel EG (2003) Prebiotics and the bioavailability of minerals and trace elements. Food Rev Int 19(4):397–422

Bonier F, Martin PR, Moore IT, Wingfield JC (2009) Do baseline glucocorticoids predict fitness? Trends Ecol Evol 24(11):634–642. https://doi.org/10.1016/j.tree.2009.04.013

Bovera F, Iannaccone F, Mastellone V, Nizza S, Lestingi A, De Martino L et al (2012) Effect of spray application of Lactobacillus plantarum on in vivo performance, caecal fermentations and haematological traits of suckling rabbits. Ital J Anim Sci 11(2):e27

Breves G, Szentkuti L, Schröder B (2001) Effects of oligosaccharides on functional parameters of the intestinal tract of growing pigs. Dtsch Tierarztl Wochenschr 108(6):246–248

Brugère C, Aguilar-Manjarrez J, Beveridge MCM, Soto D (2019) The ecosystem approach to aquaculture 10 years on—a critical review and consideration of its future role in blue growth. Rev Aquac 11(3):493–514. https://doi.org/10.1111/RAQ.12242

Cerezuela R, Cuesta A, Meseguer J, Esteban MÁ (2008) Effects of inulin on gilthead seabream (Sparus aurata L.) innate immune parameters. Fish Shellfish Immunol 24(5):663–668

Chaudhry HS, Nath K (1985) Nickel-induced hyperglycemia in the freshwater fish, Colisa fasciatus. Water Air Soil Pollut 24(2):173–176. https://doi.org/10.1007/BF00285442

Ciji A, Akhtar MS (2021) Stress management in aquaculture: a review of dietary interventions. Rev Aquac 13(4):2190–2247. https://doi.org/10.1111/raq.12565

Clotfelter ED, O'Hare EP, McNitt MM, Carpenter RE, Summers CH (2007) Serotonin decreases aggression via 5-HT1A receptors in the fighting fish Betta splendens. Pharmacol Biochem Behav 87(2):222–231

Conde-Sieira M, Chivite M, Míguez JM, Soengas JL (2018) Stress affects the mechanisms regulating appetite in teleost fish. Front Endocrinol 9:631. https://doi.org/10.3389/fendo.2018.00631

Cook KV, McConnachie SH, Gilmour KM, Hinch SG, Cooke SJ (2011) Fitness and behavioral correlates of pre-stress and stress-induced plasma cortisol titers in pink salmon (Oncorhynchus gorbuscha) upon arrival at spawning grounds. Horm Behav 60(5):489–497. https://doi.org/10.1016/j.yhbeh.2011.07.017

Cordero H, Morcillo P, Cuesta A, Brinchmann MF, Esteban MA (2016) Differential proteome profile of skin mucus of gilthead seabream (Sparus aurata) after probiotic intake and/or overcrowding stress. J Proteome 132:41–50. https://doi.org/10.1016/j.jprot.2015.11.017

Damsgård B, Mortensen A, Sommer AI (1998) Effects of infectious pancreatic necrosis virus (IPNV) on appetite and growth in Atlantic salmon, Salmo salar L. Aquaculture 163(3–4):185–193. https://doi.org/10.1016/S0044-8486(98)00242-7

Dawood MA, Koshio S, Zaineldin AI, Van Doan H, Moustafa EM, Abdel-Daim MM et al (2019) Dietary supplementation of selenium nanoparticles modulated systemic and mucosal immune status and stress resistance of red sea bream (Pagrus major). Fish Physiol Biochem 45(1):219–230. https://doi.org/10.1007/s10695-018-0556-3

Dawood MA, Eweedah NM, Moustafa EM, Shahin MG (2020) Synbiotic effects of aspergillus oryzae and β-glucan on growth and oxidative and immune responses of Nile tilapia. Oreochromis niloticus. Probiotics Antimicrob Proteins 12(1):172–183

de Campos CM, Zanuzzo FS, Gimbo RY, Favero GC, Soares MP, Pilarski F, Urbinati EC (2022) Dietary inulin modulated the cortisol response and increased the protection against pathogens in juvenile pacu (Piaractus mesopotamicus). Aquac Res 53(3):860–869

El-Saadony MT, Alagawany M, Patra AK, Kar I, Tiwari R, Dawood MA et al (2021) The functionality of probiotics in aquaculture: an overview. Fish Shellfish Immunol 117:36–52. https://doi.org/10.1016/j.fsi.2021.07.007

El-Sayed AFM, Izquierdo M (2022) The importance of vitamin E for farmed fish—a review. Rev Aquac 14(2):688–703

Emami NK, Samie A, Rahmani HR, Ruiz-Feria CA (2012) The effect of peppermint essential oil and fructooligosaccharides, as alternatives to virginiamycin, on growth performance, digestibility, gut morphology and immune response of male broilers. Anim Feed Sci Technol 175(1–2):57–64

Eshaghzadeh H, Hoseinifar SH, Vahabzadeh H, Ringø E (2015) The effects of dietary inulin on growth performances, survival and digestive enzyme activities of common carp (C yprinus carpio) fry. Aquac Nutr 21(2):242–247

Espe M, Holen E (2013) Taurine attenuates apoptosis in primary liver cells isolated from Atlantic salmon (Salmo salar). Br J Nutr 110(1):20–28

FAO (2020) The state of world fisheries and aquaculture 2020. Sustainability in action. FAO, Rome. https://doi.org/10.4060/ca9229en

Flores-Maltos DA, Mussatto SI, Contreras-Esquivel JC, Rodríguez-Herrera R, Teixeira JA, Aguilar CN (2016) Biotechnological production and application of fructooligosaccharides. Crit Rev Biotechnol 36(2):259–267

Foo JTW, Lam TJ (1993a) Retardation of ovarian growth and depression of serum steroid levels in the tilapia, Oreochromis mossambicus, by cortisol implantation. Aquaculture 115(1–2):133–143

Foo JTW, Lam TJ (1993b) The serum cortisol response to handling stress and the effect of cortisol implantation on testosterone level in the tilapia, Oreochromis mossambicus. Aquaculture 115(1–2):145–158. https://doi.org/10.1016/0044-8486(93)90365-6

Fox HE, White SA, Kao MHF, Fernald RD (1997) Stress and dominance in a social fish. J Neurosci 17(16):6463–6469. https://doi.org/10.1523/jneurosci.17-16-06463.1997

Gatlin III DM, Li P, Wang X, Burr GS, Castille F, Lawrence AL (2006) Potential application of prebiotics in aquaculture. En: Editores: L. Elizabeth Cruz Suárez, Denis Ricque Marie, Mireya Tapia Salazar, Martha G. Nieto López, David A. Villarreal Cavazos, Ana C. Puello Cruz y Armando García Ortega. Avances en Nutrición Acuícola VIII. VIII Simposium Internacional de Nutrición Acuícola. 15 - 17 Noviembre. Universidad Autónoma de Nuevo León, Monterrey, Nuevo León, México. ISBN 970-694-333-5

Gelibolu S, Yanar Y, Genc MA, Genc E (2018) The effect of mannan-oligosaccharide (MOS) as a feed supplement on growth and some blood parameters of Gilthead Sea bream (Sparus aurata). Turk J Fish Aquat Sci 18(6):817–823

Gibson GR, Rastall RA (2006) Prebiotics: development & application. John Wiley & Sons, West Sussex, pp 101–110. https://doi.org/10.1002/9780470023150

Gibson GR, Scott KP, Rastall RA, Tuohy KM, Hotchkiss A, Dubert-Ferrandon A et al (2010) Dietary prebiotics: current status and new definition. Food Sci Technol Bull Funct Foods 7 (1):1–19

Gibson GR, Roberfroid MB (1995) Dietary modulation of the human colonic microbiota: introducing the concept of prebiotics. J Nutr 125(6):1401–1412

Giri SS, Sukumaran V, Sen SS, Vinumonia J, Banu BN, Jena PK (2011) Antagonistic activity of cellular components of potential probiotic bacteria, isolated from the gut of Labeo rohita, against Aeromonas hydrophila. Probiotics Antimicrob Proteins 3(3):214–222. https://doi.org/10.1007/s12602-011-9078-3

Gobi N, Vaseeharan B, Chen JC, Rekha R, Vijayakumar S, Anjugam M, Iswarya A (2018) Dietary supplementation of probiotic Bacillus licheniformis Dahb1 improves growth performance, mucus and serum immune parameters, antioxidant enzyme activity as well as resistance against Aeromonas hydrophila in tilapia Oreochromis mossambicus. Fish Shellfish Immunol 74:501–508. https://doi.org/10.1016/j.fsi.2017.12.066

Gupta A, Gupta SK, Priyam M, Siddik MAB, Kumar N, Mishra PK, Pattanayak A (2021) Immunomodulation by dietary supplements: a preventive health strategy for sustainable aquaculture of tropical freshwater fish, Labeo rohita (Hamilton, 1822). Rev Aquac 13(4):2364–2394. https://doi.org/10.1111/raq.12581

Höglund E, Bakke MJ, Øverli Ø, Winberg S, Nilsson GE (2005) Suppression of aggressive behavior in juvenile Atlantic cod (Gadus morhua) by l-tryptophan supplementation. Aquaculture 249(1–4):525–531

Höglund E, Sørensen C, Bakke MJ, Nilsson GE, Øverli Ø (2007) Attenuation of stress-induced anorexia in brown trout (Salmo trutta) by pre-treatment with dietary L-tryptophan. Br J Nutr 97(4):786–789

Hoseinifar SH, Esteban MÁ, Cuesta A, Sun YZ (2015) Prebiotics and fish immune response: a review of current knowledge and future perspectives. Rev Fish Sci Aquac 23(4):315–328

Hoseinifar SH, Yousefi S, Van Doan H, Ashouri G, Gioacchini G, Maradonna F, Carnevali O (2020) Oxidative stress and antioxidant defense in fish: the implications of probiotic, prebiotic, and synbiotics. Rev Fish Sci Aquac 29(2):198–217. https://doi.org/10.1080/23308249.2020.1795616

Hu Z, Li R, Xia X, Yu C, Fan X, Zhao Y (2020) A method overview in smart aquaculture. Environ Monit Assess 192(8):1–25. https://doi.org/10.1007/s10661-020-08409-9

Huffman LS, Hinz FI, Wojcik S, Aubin-Horth N, Hofmann HA (2015) Arginine vasotocin regulates social ascent in the African cichlid fish Astatotilapia burtoni. Gen Comp Endocrinol 212:106–113. https://doi.org/10.1016/j.ygcen.2014.03.004

Ibrahem MD, Fathi M, Mesalhy S, Abd El-Aty AM (2010) Effect of dietary supplementation of inulin and vitamin C on the growth, hematology, innate immunity, and resistance of Nile tilapia (Oreochromis niloticus). Fish Shellfish Immunol 29(2):241–246

Ibrahim OO (2018) Functional oligosaccharides: chemicals structure, manufacturing, health benefits, applications and regulations. J Food Chem Nanotechnol 4(4):65–76

Irianto A, Austin B (2003) Use of dead probiotic cells to control furunculosis in rainbow trout, Oncorhynchus mykiss (Walbaum). J Fish Dis 26(1):59–62

Jahangiri L, Esteban MÁ (2018) Administration of probiotics in the water in finfish aquaculture systems: a review. Aust Fish 3(3):1–13. https://doi.org/10.3390/fishes3030033

Jami MJ, Kenari AA, Paknejad H, Mohseni M (2019) Effects of dietary b-glucan, mannan oligosaccharide, lactobacillus plantarum and their combinations on growth performance, immunity and immune related gene expression of Caspian trout, Salmo trutta caspius (Kessler, 1877). Fish Shellfish Immunol 91:202–208

Javed M, Ahmad MI, Usmani N, Ahmad M (2017) Multiple biomarker responses (serum biochemistry, oxidative stress, genotoxicity, and histopathology) in Channa punctatus exposed to heavy metal loaded wastewater/704/172/4081/631/601 article. Sci Rep 7(1):1–11. https://doi.org/10.1038/s41598-017-01749-6

Khodadadi A, Malekinejad H, Hosseini MS (2021) Effects of diet supplementation with different level of Celmanax®(Saccharomyces cerevisiae cell wall with Mannan-oligosaccharides) on health, environmental stress and Yersiniosis in Oncorhynchus mykiss. Iran J Aquat Anim Health 7(2):44–60

Khosravi-Katuli K, Mohammadi Y, Ranjbaran M, Ghanaatian H, Khazaali A, Paknejad H, Santander J (2021) Effects of mannan oligosaccharide and synbiotic supplementation on growth performance and immune response of Gilthead Sea Bream (Sparus aurata) before and after thermal stress. Aquac Res 52(8):3745–3756

Kitamura S (1965) Studies on vitamin requirements of rainbow trout, Salmo gairdneri-I. on the ascorbic acid. Bull Jpn Soc Sci Fish 31:818–826

Kim JJ, Lee SB, Park JK, Yoo YD (2010) TNF-α-induced ROS production triggering apoptosis is directly linked to Romo1 and Bcl-XL. Cell Death Differ 17(9):1420–1434

Kim YR, Kim EY, Choi SY, Hossain MT, Oh RK, Heo WS et al (2012) Effect of a probiotic strain, enterococcus faecium, on the immune responses of olive flounder (Paralichthys olivaceus). J Microbiol Biotechnol 22(4):526–529

Kozicz T (2007) CRF and CRF-related peptides in stress adaptation: from invertebrates to man. Gen Comp Endocrinol 153(1–3):198–199. https://doi.org/10.1016/j.ygcen.2007.06.007

Kumar R, Mukherjee SC, Prasad KP, Pal AK (2006) Evaluation of Bacillus subtilis as a probiotic to Indian major carp Labeo rohita (Ham.). Aquac Res 37(12):1215–1221. https://doi.org/10.1111/j.1365-2109.2006.01551.x

Kumar P, Jain KK, Sardar P, Jayant M, Tok NC (2018) Effect of dietary synbiotics on growth performance, body composition, digestive enzyme activity, and gut microbiota in Cirrhinus mrigala (ham.) fingerlings. Aquacult Nutr 24(3):921–929

Kümmerer K (2009) Antibiotics in the aquatic environment—a review—part I. Chemosphere 75: 417–434. https://doi.org/10.1016/j.chemosphere.2008.11.086

Leitz T (1987) Social control of testicular steroidogenic capacities in the Siamese fighting fish Betta splendens Regan. J Exp Zool 244(3):473–478. https://doi.org/10.1002/jez.1402440313

Lepage O, Tottmar O, Winberg S (2002) Elevated dietary intake of L-tryptophan counteracts the stress-induced elevation of plasma cortisol in rainbow trout (Oncorhynchus mykiss). J Exp Biol 205(23):3679–3687

Lu ZY, Feng L, Jiang WD, Wu P, Liu Y, Jin XW, Tang L (2022) An antioxidant supplement function exploration: Rescue of Intestinal Structure Injury by Mannan oligosaccharides after Aeromonas hydrophila infection in grass carp (Ctenopharyngodon idella). Antioxidants 2022(11):806

Magouz FI, Bassuini MI, Khalafalla MM, Abbas R, Sewilam H, Aboelenin SM et al (2021) Mannan oligosaccharide enhanced the growth rate, digestive enzyme activity, carcass composition, and blood chemistry of Thinlip grey mullet (Liza ramada). Animals 11(12):3559

Mahious AS, Gatesoupe FJ, Hervi M, Metailler R, Ollevier F (2006a) Effect of dietary inulin and oligosaccharides as prebiotics for weaning turbot, Psetta maxima (Linnaeus, C. 1758). Aquac Int 14(3):219–229

Mahious AS, Van Loo J, Ollevier F (2006b) Impact of the prebiotics, inulin and oligofructose on microbial fermentation in the spiral valve of Siberian sturgeon (Acipenser baerii). World Aquaculture Society

Marcinkiewicz J, Kontny E (2014) Taurine and inflammatory diseases. Amino Acids 46(1):7–20

Martínez Cruz P, Ibáñez AL, Monroy Hermosillo OA, Ramírez Saad HC (2012) Use of probiotics in aquaculture. Int Scholarly Res Not 2012. https://doi.org/10.5402/2012/916845

Maruska KP, Fernald RD (2015) Social regulation of gene expression in the African cichlid fish Astatotilapia burtoni. In: Handbook of molecular psychology, pp 52–78

Merrifield DL, Dimitroglou A, Foey A, Davies SJ, Baker RT, Bøgwald J, Ringø E (2010) The current status and future focus of probiotic and prebiotic applications for salmonids. Aquaculture 302(1–2):1–18

Mohapatra S, Chakraborty T, Kumar V, DeBoeck G, Mohanta KN (2013) Aquaculture and stress management: a review of probiotic intervention. J Anim Physiol Anim Nutr 97(3):405–430

Montero D, Tort L, Robaina L, Vergara JM, Izquierdo MS (2001) Low vitamin E in the diet reduces stress resistance of gilthead seabream (Sparus aurata) juveniles. Fish Shellfish Immunol 11(6): 473–490

Mouriño JLP, Do Nascimento Vieira F, Jatobá AB, Da Silva BC, Jesus GFA, Seiffert WQ, Martins ML (2012) Effect of dietary supplementation of inulin and W. cibaria on haemato-immunological parameters of hybrid surubim (Pseudoplatystoma sp). Aquac Nutr 18(1):73–80

Mussatto SI (2009) Biotechnological potential of brewing industry by-products. In: Biotechnology for agroindustrial residues utilisation. Springer, Dordrecht, pp 313–326

Nahid Akter M, Parvez I, Parveen Patwary Z, Akter, C. MN (2016) Beneficial effects of probiotics in aquaculture. Int J Fish Aquat 4(5):494–499. www.fisheriesjournal.com

Nikinmaa M (1992) How does environmental pollution affect red cell function in fish? Aquat Toxicol 22(4):227–238. https://doi.org/10.1016/0166-445X(92)90042-L

Nikinmaa M (2003) Gas transport. Jpn J Thorac Dis 15(9):489–509. https://doi.org/10.1007/978-3-662-05181-8_20

Nopvichai C, Charoenwongpaiboon T, Luengluepunya N, Ito K, Muanprasat C, Pichyangkura R (2019) Production and purification of mannan oligosaccharide with epithelial tight junction enhancing activity. PeerJ 7:e7206

Oliva-Teles A (2012) Nutrition and health of aquaculture fish. J Fish Dis 35(2):83–108. https://doi.org/10.1111/j.1365-2761.2011.01333.x

Olsen RE, Myklebust R, Kryvi H, Mayhew TM, Ringø E (2001) Damaging effect of dietary inulin on intestinal enterocytes in Arctic charr (Salvelinus alpinus L.). Aquac Res 32(11):931–934

Ortiz LT, Rebolé A, Velasco S, Rodríguez ML, Treviño J, Tejedor JL, Alzueta C (2013) Effects of inulin and fructooligosaccharides on growth performance, body chemical composition and intestinal microbiota of farmed rainbow trout (O ncorhynchus mykiss). Aquac Nutr 19 (4):475–482

Pankhurst NW (2011) The endocrinology of stress in fish: an environmental perspective. Gen Comp Endocrinol 170(2):265–275. https://doi.org/10.1016/j.ygcen.2010.07.017

Pankhurst NW, Van Der Kraak G (1995) Evidence that the inhibitory effects of stress on reproduction in teleost fish are not mediated by the action of cortisol on ovarian steroidogenesis. Gen Comp Endocrinol 99(3):249–257. https://doi.org/10.1006/GCEN.1995.1108

Pankhurst NW, Van Der Kraak G (2000) Evidence that acute stress inhibits ovarian steroidogenesis in rainbow trout in vivo, through the action of cortisol. Gen Comp Endocrinol 117(2):225–237. https://doi.org/10.1006/gcen.1999.7401

Peixoto MJ, Domingues A, Batista S, Gonçalves JFM, Gomes AM, Cunha S et al (2018) Physio-pathological responses of sole (Solea senegalensis) subjected to bacterial infection and handling stress after probiotic treatment with autochthonous bacteria. Fish Shellfish Immunol 83:348–358. https://doi.org/10.1016/j.fsi.2018.09.045

Pickering AD, Stewart A (1984) Acclimation of the interrenal tissue of the brown trout, Salmo trutta L., to chronic crowding stress. J Fish Biol 24(6):731–740. https://doi.org/10.1111/J.1095-8649.1984.TB04844.X

Ramesh D, Vinothkanna A, Rai AK, Vignesh VS (2015) Isolation of potential probiotic Bacillus spp. and assessment of their subcellular components to induce immune responses in Labeo rohita against Aeromonas hydrophila. Fish Shellfish Immunol 45(2):268–276. https://doi.org/10.1016/j.fsi.2015.04.018

Randall DJ, Ferry SF (1992) 4 Catecholamines. In: Fish physiology, vol 12. Academic Press, pp 255–300. https://doi.org/10.1016/S1546-5098(08)60011-4

Refstie S, Bakke-McKellep AM, Penn MH, Sundby A, Shearer KD, Krogdahl Å (2006) Capacity for digestive hydrolysis and amino acid absorption in Atlantic salmon (Salmo salar) fed diets with soybean meal or inulin with or without addition of antibiotics. Aquaculture 261(1):392–406. https://doi.org/10.1016/j.aquaculture.2006.08.005

Reid, Scott D, Moon TW, Perry STEVEF (1991) Characterization of beta-adrenoreceptors of rainbow trout (Oncorhynchus mykiss) erythrocytes. J Exp Biol 158:199–216. Retrieved from https://pubmed.ncbi.nlm.nih.gov/1655944/

Reid SG, Bernier NJ, Perry SF (1998) The adrenergic stress response in fish: control of catecholamine storage and release. Comp Biochem Physiol C Pharmacol Toxicol Endocrinol 120(1): 1–27. https://doi.org/10.1016/S0742-8413(98)00037-1

Ren Z, Wang S, Cai Y, Wu Y, Tian L, Wang S, Zhou Y (2020) Effects of dietary mannan oligosaccharide supplementation on growth performance, antioxidant capacity, non-specific immunity and immune-related gene expression of juvenile hybrid grouper (Epinephelus lanceolatus♂× Epinephelus fuscoguttatus♀). Aquaculture 523:735195

Reza A, Abdolmajid H, Abbas M, Abdolmohammad AK (2009) Effect of dietary prebiotic inulin on growth performance, intestinal microflora, body composition and hematological parameters of juvenile beluga, Huso huso (Linnaeus, 1758). J World Aquacult Soc 40(6):771–779

Ringø E, Sperstad S, Myklebust R, Refstie S, Krogdahl Å (2006) Characterisation of the microbiota associated with intestine of Atlantic cod (Gadus morhua L.): the effect of fish meal, standard soybean meal and a bioprocessed soybean meal. Aquaculture 261(3):829–841. https://doi.org/10.1016/j.aquaculture.2006.06.030

Ringø E, Olsen RE, Gifstad TØ, Dalmo RA, Amlund H, Hemre GI, Bakke AM (2010) Prebiotics in aquaculture: a review. Aquac Nutr 16(2):117–136

Roberfroid MB (2001) Prebiotics: preferential substrates for specific germs? Am J Clin Nutr 73 (2):406s–409s

Robinson DR, Prickett JD, Polisson R, Steinberg AD, Levine L (1985) The protective effect of dietary fish oil on murine lupus. Prostaglandins 30(1):51–75

Rodriguez-Estrada U, Satoh S, Haga Y, Fushimi H, Sweetman J (2009) Effects of single and combined supplementation of enterococcus faecalis, mannan oligosaccharide, and polyhydroxybutyrate acid on growth performance and immune response of rainbow trout Oncorhynchus mykiss. Aquacult Sci 57(4):609–617

Rousseau K, Prunet P, Dufour S (2021) Special features of neuroendocrine interactions between stress and reproduction in teleosts. Gen Comp Endocrinol 300:113634. https://doi.org/10.1016/j.ygcen.2020.113634

Sabater-Molina M, Larqué E, Torrella F, Zamora S (2009) Dietary fructooligosaccharides and potential benefits on health. J Physiol Biochem 65(3):315–328

Sahoo PK, Rauta PR, Mohanty BR, Mahapatra KD, Saha JN, Rye M, Eknath AE (2011) Selection for improved resistance to Aeromonas hydrophila in Indian major carp Labeo rohita: survival and innate immune responses in first generation of resistant and susceptible lines. Fish Shellfish Immunol 31(3):432–438. https://doi.org/10.1016/j.fsi.2011.06.014

Sahu MK, Swarnakumar NS, Sivakumar K, Thangaradjou T, Kannan L (2008) Probiotics in aquaculture: importance and future perspectives. Indian J Microbiol 48(3):299–308. https://doi.org/10.1007/s12088-008-0024-3

Sampaio FD, Freire CA (2016) An overview of stress physiology of fish transport: changes in water quality as a function of transport duration. Fish Fish 17(4):1055–1072

Sandnes K (1991) Vitamin C in fish nutrition—a review. FiskDir Skr, Ser Ernering IV(1):3–32

Schreck CB (2009) Accumulation and long-term effects of stress in fish. In: The biology of animal stress: basic principles and implications for animal welfare, pp 147–158. https://doi.org/10.1079/9780851993591.0147

Schreck CB, Bradford CS (1990) Interrenal corticosteroid production: potential regulation by the immune system in the salmonid. Prog Clin Biol Res 342:480–486. https://pubmed.ncbi.nlm.nih.gov/2381950/

Schreck CB, Tort L (2016) The concept of stress in fish. Fish Physiol 35:1–34. https://doi.org/10.1016/B978-0-12-802728-8.00001-1

Selye H (1950) Stress and the general adaptation syndrome. Br Med J 1(4667):1383–1392. https://doi.org/10.1136/BMJ.1.4667.1383

Selye H (1976) Stress without distress. In: Psychopathology of human adaptation, pp 137–146. https://doi.org/10.1007/978-1-4684-2238-2_9

Serradell A, Torrecillas S, Makol A, Valdenegro V, Fernández-Montero A, Acosta F, Montero D (2020) Prebiotics and phytogenics functional additives in low fish meal and fish oil based diets for European sea bass (Dicentrarchus labrax): effects on stress and immune responses. Fish Shellfish Immunol 100:219–229

Silva DG, Cooper PD, Petrovsky N (2004) Inulin-derived adjuvants efficiently promote both Th1 and Th2 immune responses. Immunol Cell Biol 82(6):611–616

Singh SK, Tiwari VK, Chadha NK, Prakash C et al (2015) Effect of Bacillus circulans and fructooligosaccharide supplementation on growth and haemato-immunological function of Labeo rohita (Hamilton, 1822) fingerlings exposed to sub-lethal nitrite stress. Isr J Aquacult Bamidgeh 67:20673

Singh SK, Tiwari VK, Chadha NK, Munilkumar S, Prakash C, Pawar NA (2019) Effect of dietary synbiotic supplementation on growth, immune and physiological status of Labeo rohita juveniles exposed to low pH stress. Fish Shellfish Immunol 91:358–368

Singh SK, Tiwari VK, Munilkumar S, Prakash C, Chadha NK, Biswas P (2021) Effect of dietary synbiotic on serum biochemistry and anti-oxidative function of Labeo rohita fingerlings exposed to sub-lethal nitrite stress. Indian J Anim Health 60(2):253–261

Sivasubramanian K, Ravichandran S, Kavitha R (2012) Isolation and characterization of gut micro biota from some estuarine fishes. Mar Sci 2(2):1–6. https://doi.org/10.5923/j.ms.20120202.01

Soares MP, Oliveira FC, Cardoso IL, Urbinati EC, de Campos CM, Hisano H (2018) Glucan-MOS® improved growth and innate immunity in pacu stressed and experimentally infected with Aeromonas hydrophila. Fish Shellfish Immunol 73:133–140

Soleimani N, Hoseinifar SH, Merrifield DL, Barati M, Abadi ZH (2012) Dietary supplementation of fructooligosaccharide (FOS) improves the innate immune response, stress resistance, digestive enzyme activities, and growth performance of Caspian roach (Rutilus rutilus) fry. Fish Shellfish Immunol 32(2):316–321

Tang Y, Han L, Chen X, Xie M, Kong W, Wu Z (2019) Dietary supplementation of probiotic Bacillus subtilis affects antioxidant defenses and immune response in grass carp under Aeromonas hydrophila challenge. Probiotics Antimicrob Proteins 11(2):545–558. https://doi.org/10.1007/s12602-018-9409-8

Taoka Y, Maeda H, Jo JY, Jeon MJ, Bai SC, Lee WJ et al (2006) Growth, stress tolerance and non-specific immune response of Japanese flounder Paralichthys olivaceus to probiotics in a closed recirculating system. Fish Sci 72(2):310–321. https://doi.org/10.1111/j.1444-2906.2006.01152.x

Teirlynck E, Gussem MDE, Dewulf J, Haesebrouck F, Ducatelle R, Van Immerseel F (2011) Morphometric evaluation of “dysbacteriosis” in broilers. Avian Pathol 40(2):139–144

Tiengtam N, Paengkoum P, Sirivoharn S, Phonsiri K, Boonanuntanasarn S (2017) The effects of dietary inulin and Jerusalem artichoke (Helianthus tuberosus) tuber on the growth performance, haematological, blood chemical and immune parameters of Nile tilapia (Oreochromis niloticus) fingerlings. Aquac Res 48(10):5280–5288

Torrecillas S, Makol A, Caballero MJ, Montero D, Dhanasiri AKS, Sweetman J, Izquierdo M (2012) Effects on mortality and stress response in European sea bass, Dicentrarchus labrax (L.), fed mannan oligosaccharides (MOS) after vibrio anguillarum exposure. J Fish Dis 35(8): 591–602

Trichet VV (2010) Nutrition and immunity: an update. Aquacult Res 41(3):356–372. https://doi.org/10.1111/j.1365-2109.2009.02374.x

Trushenski JT, Kohler CC (2007) Influence of stress and dietary natural-source vitamin E on nonspecific immunocompetence, tissue tocopherol composition, and postslaughter fillet oxidative stability in sunshine bass. N Am J Aquac 69(4):330–339

Vaughan D, Yoshiyama R, Breck J, DeAngelis D (1982) Review and analysis of existing modeling approach for assessing population-level effects of multiple stresses on fish and shellfish. Environmental sciences division publication, no. 1979. https://www.osti.gov/biblio/6872040

Volkoff H, Canosa LF, Unniappan S, Cerdá-Reverter JM, Bernier NJ, Kelly SP, Peter RE (2005) Neuropeptides and the control of food intake in fish. Gen Comp Endocrinol 142(1–2):3–19. https://doi.org/10.1016/j.ygcen.2004.11.001

Wang WS, Wang DH (1997) Enhancement of the resistance of tilapia and grass carp to experimental Aeromonas hydrophila and Edwardsiella tarda infections by several polysaccharides. Comp Immunol Microbiol Infect Dis 20(3):261–270

Westring CG, Ando H, Kitahashi T, Bhandari RK, Ueda H, Urano A, Danielson PB (2008) Seasonal changes in CRF-I and urotensin I transcript levels in masu salmon: correlation with cortisol secretion during spawning. Gen Comp Endocrinol 155(1):126–140. https://doi.org/10.1016/j.ygcen.2007.03.013

Ye JD, Wang K, Li FD, Sun YZ (2011) Single or combined effects of fructo-and mannan oligosaccharide supplements and Bacillus clausii on the growth, feed utilization, body composition, digestive enzyme activity, innate immune response, and lipid metabolism of the Japanese flounder Paralichthys olivaceus. Aquacult Nutr 17(4):e902–e911

Yousefian M, Amiri MS (2009) A review of the use of prebiotic in aquaculture for fish and shrimp. Afr J Biotechnol 8(25)

Zhang CN, Li XF, Jiang GZ, Zhang DD, Tian HY, Li JY, Liu WB (2014a) Effects of dietary fructooligosaccharide levels and feeding modes on growth, immune responses, antioxidant capability and disease resistance of blunt snout bream (Megalobrama amblycephala). Fish Shellfish Immunol 41(2):560–569

Zhang Q, Yu H, Tong T, Tong W, Dong L, Xu M, Wang Z (2014b) Dietary supplementation of Bacillus subtilis and fructooligosaccharide enhance the growth, non-specific immunity of juvenile ovate pompano, Trachinotus ovatus and its disease resistance against Vibrio vulnificus. Fish Shellfish Immunol 38(1):7–14

Zhang CN, Li XF, Xu WN, Zhang DD, Lu KL, Wang LN, Liu WB (2015) Combined effects of dietary fructooligosaccharide and bacillus licheniformis on growth performance, body composition, intestinal enzymes activities and gut histology of triangular bream (Megalobrama terminalis). Aquacult Nutr 21(5):755–766

Zhang C, Wang J, Qi Q, Yang L, Sun P, Yuan X (2021) Modulatory effect of fructooligosaccharide against triphenyltin-induced oxidative stress and immune suppression in goldfish (Carassius auratus). Ecotoxicol Environ Saf 212:111966

Zhou Q, Wang L, Wang H, Xie F, Wang T (2012) Effect of dietary vitamin C on the growth performance and innate immunity of juvenile cobia (Rachycentron canadum). Fish Shellfish Immunol 32(6):969–975. https://doi.org/10.1016/j.fsi.2012.01.024

Zhou L, Zhang J, Yan M, Tang S, Wang X, Qin JG et al (2020) Inulin alleviates hypersaline-stress induced oxidative stress and dysbiosis of gut microbiota in Nile tilapia (Oreochromis niloticus). Aquaculture 529:735681

Zorriehzahra MJ, Delshad ST, Adel M, Tiwari R, Karthik K, Dhama K, Lazado CC (2016) Probiotics as beneficial microbes in aquaculture: an update on their multiple modes of action: a review. Vet Q 36(4):228–241. https://doi.org/10.1080/01652176.2016.1172132

Dealing the Hardship in Aquaculture Nutrition in a Changing Climatic Condition

Gour Hari Pailan and Gouranga Biswas

Abstract

Aquaculture is the only option available to supply the increasing fish demand globally, as there is a declining trend in capture fisheries. Major aquaculture operations across the world largely rely on the ambient environment and ecosystem performances, indicating their vulnerability to climate adversities. Therefore, climate change's effects on aquaculture cannot be ruled out. The modern aquaculture operations are mostly feed-based production systems, where feed is one of the major inputs constituting around 50–60% of operational expenditure. In the changing climatic situations, management of aquaculture nutrition that includes sourcing feedstuffs and feed, feeding methods, and supply of nutrients to farmed animals from allochthonous and autochthonous sources has been predicted to be affected. Suitable adaptive responses to deal with these climate change issues on aquaculture nutrition need to be made available based on real-time information collected continuously. Quality and quantity of diets could help species deal with the climate change biotic and abiotic stressors by meeting the enhancing energy and nutrient requirement associated with the adaptation responses. Therefore, aquaculture nutritional management will be a challenging and complex issue to address. In this direction, research support for adaptive strategies will be necessary. The aquaculture sector should move beyond short-term dealing strategies, rather there should be planned and long-term climate change adaptation and mitigation responses in place with the involvement of public and private

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stakeholders on regional importance basis. This chapter covers concise information on the consequences of climate change on nutrition, feed, and feeding of fish, adaptation or coping strategies, and projected scenarios of feed ingredients and feed availability for aquaculture.

Keywords

Climate change effects · Adaptive strategies · Feeding management · Feedstuff sourcing · Nutritional management

1 Introduction

The effects of climate change are going to impose several hindrances on aquaculture operations. Modern aquaculture operations are mostly fed systems where management of nutrition for target animals is given much attention. Intensification of aquaculture has a major role to increase fish production toward fulfilling the accelerating demand due to population rise. Intensive or modern aquaculture systems are dependent on an external supply of feed containing balanced nutrients for farmed species. It is presumed that to maintain the current annual growth rate of 8–10% of the aquaculture sector to 2030 or beyond, the availability of nutrient resources and feeds will be required to grow simultaneously. In pond aquaculture systems, fish have traditionally been raised on natural food items (microorganisms, phyto- and zooplankton) augmented by the application of agricultural wastes (Brummett and Beveridge 2016). However, with the enhanced use of feeds, fish biomass production per unit area of land and water has been increased, and almost 70% of fish production from aquaculture is based on feed supply (Tacon et al. 2011). As natural fish food items are influenced by temperature, sunlight, and nutrient supply, climate change, namely temperature rise will directly affect productivity and fish growth for warm-water fishes, such as catfish, tilapia, Indian major carps and Chinese carps. Moreover, sporadic rainfall might have effects on this autochthonous productivity and thus on fish production (Allison et al. 2009). The availability of crop-based feedstuffs and the major animal source ingredient, fishmeal will be affected due to climate alteration. Therefore, Asian aquaculture of carps, catfish, and tilapias that largely depend on the moist or semi-moist dough and dried pellets will be impacted. As nutritionally balanced feeds are being increasingly used, the availability of cost-effective feed ingredients is becoming ambitious during the new climatic regime. While aquaculture is expected to grow by at least 50% by 2030 (Hall et al. 2011; World Bank 2013; WRI 2014), its dependency on feeds is also expected to increase at a similar pace, and thereby growth of this sector will rely on technology development, market policy, demand for feedstuffs and impacts of climate change (WRI 2014). Globally, various aquaculture systems are dependent on the ambient environment and ecosystem performances to a great extent. It indicates the existence of the underlying vulnerability of aquaculture to climate change consequences. However, in the changing climatic condition, aquaculture may possess a better adaptive capacity in terms of managing stock in captivity than that of wild species (Richards et al. 2015; Oyebola and Olatunde 2019). Therefore, based on this advantage, it is important to develop adaptive strategies by identifying and learning the responses to climate change (Cinner et al. 2018). Correct understanding of the effects of climate change on biological and ecosystem responses, resource management, and economic affairs in aquaculture will be a valid preparedness (Reid et al. 2019). Once the effects of climate change on aquaculture are well understood, novel and innovative coping strategies could be developed after identifying the research questions. In this context of changing climatic situation, maintaining the aquaculture growth becomes a very challenging and complex task, especially in the nutrition and feed management of farmed aquatic species. In this background, this chapter covers information on the impacts of climate change on nutrition, feed, and feeding of fish, adaptation or coping strategies, and related projection.

2 Climate Change Impacts on Aquaculture Nutrition

As aquaculture is mostly a climate-dependent sector, climate change is a major threat to its performance in increasing fish production (Fig. 1). Climate change has already been reported to influence ecosystems and the production level of aquaculture (Brander 2007; De Silva and Soto 2009). A major consequence of climate change, the worldwide scarcity of freshwater affects aquaculture productivity and causes high water demand (Hanjra and Qureshi 2010; Turral et al. 2011). Likewise, nutrition and feeding in aquaculture is also facing hardship. As the major share of global aquaculture production, around 70% comes from feed-based systems (Tacon and Metian 2015), climate change has direct effects on the availability of feed ingredients and feeding management (De Silva and Soto 2009; Brugère 2015; Shelton 2014). As a consequence of climate change, crop production will be affected by changes in crop quantity and quality. Crop-based feed ingredients have become an integral part of fish feed, as they serve as sources of energy and act as binders to maintain the pelleting stability in water until consumption. The conventional crops used in the production of aquaculture feeds are soybean, rapeseed, maize, rice, and wheat bran. Climate change will have considerable impacts on these crops (Raza et al. 2019) and thereby, on the aquafeed production and use. In spite of research advancements in the identification and utilization of unconventional feedstuffs, small pelagic fishes still remain to be a major ingredient for aquafeed preparation (De Silva and Soto 2009). These small fishes or bycatch fisheries shared around 17% of global fish landing in 2014 (Tacon and Metian 2015). Moreover, bycatch fisheries were found to be affected by climate (Merino et al. 2010; Lindegren et al. 2013; Buchheister et al. 2016). Therefore, availability of these fishes as a major source of fishmeal is jeopardized by climate change and thus will indirectly affect aquaculture production. Natural fish food organisms, such as phyto- and zooplanktons, crustaceans and bivalve molluscs are sensitive to environment (Wikfors and Ohno 2001) and climate change may also cause detrimental effects on them, consequently aquaculture performance will be depleted. Oceans with warmer water and more

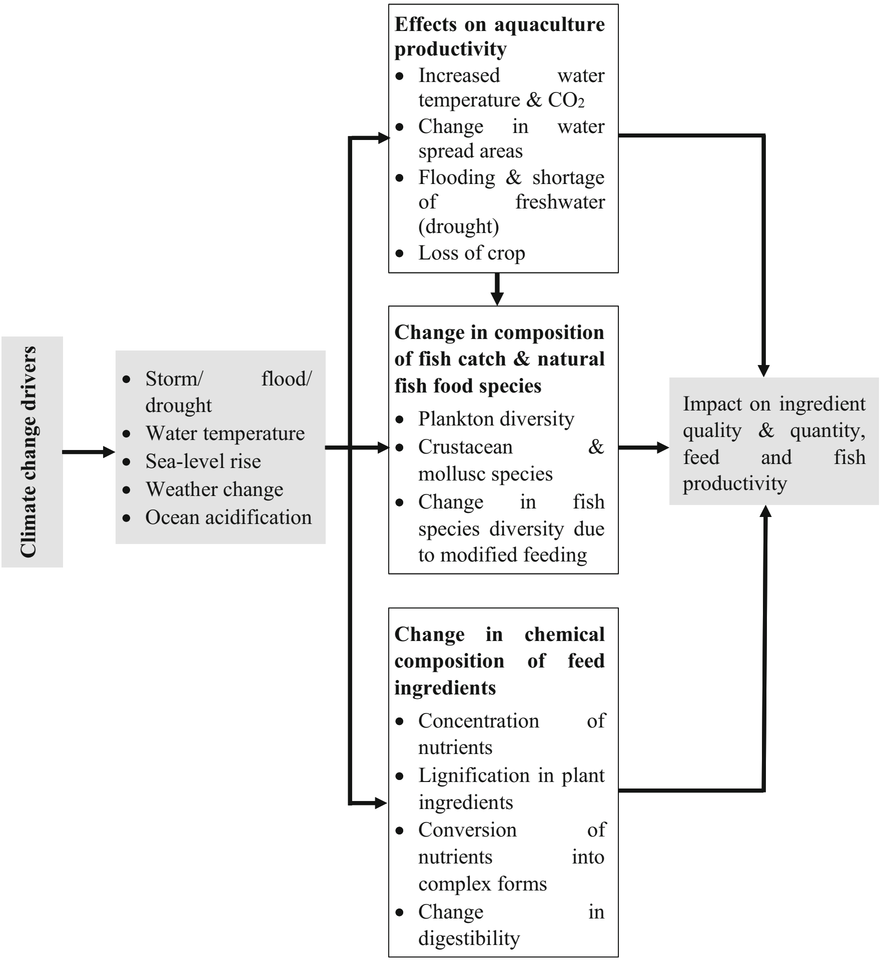

Fig. 1 A simplified flow chart depicting the pathways of climate change effects on aquaculture nutrition, feed management, and productivity

thermal stratification may reduce the phytoplankton species diversity with less adaptive ability (Acevedo-Trejos et al. 2014) and drive away the temperate species towards poles (Hallegraeff 2010).

The impacts of climate change could be location-specific (Doney 2006) and some of the aquaculture species, such as filter-feeding shellfishes may get benefitted in the environment where a nutrient deficiency exists at present (De Silva and Soto 2009). As an impact of global warming, there could be a probable reduction in omega-3 fatty acid (FA) level in phytoplankton that serves as the repository of omega-3 FA in aquatic ecosystems (Hixson and Arts 2016), which in turn will affect the supply of this important FA content in aquafeeds.

3 Adaptation Strategies Related to Nutrition Management

As an important adaptation strategy to climate change, it is necessary to enhance fish production with less or zero environmental footprints. There should be positive growth in the aquaculture sector with a considerable reduction of environmental impacts simultaneously. Among the adaptation strategies to climate change, the management of nutrition and feeding the aquaculture species is one of the most challenging ones.

3.1 Quantity and Quality of Diet for Climate Adaptive Responses

Acclimatization of organisms to environmental and biological adversities requires more energy to spend. So, nutrition can play a role in the adaptation mechanism. In the case of some mollusc species, effects of climate change stressors, like ocean acidification have been recorded and no effects on energy ingress and assimilation in the presence of adequate food supply were reported (Parker et al. 2013; Timmins-Schiffman et al. 2013). Adequate food availability could enhance tolerance levels to high pCO_2 and low pH in blue mussel *Mytilus edulis* (Melzner et al. 2011; Thomsen et al. 2013) and Pacific oyster *Crassostrea gigas* larvae (Timmins-Schiffman et al. 2013). Likewise, adaptive responses to warm water exposure have been described in several aquatic species. Shellfish species, such as California mussel *Mytilus californianus* (Fitzgerald-Dehoog et al. 2012) and juvenile South African abalone *Haliotis midae* (Vosloo et al. 2013) had better survival and acclimatization to heat shock and warm water stress in the presence of abundant foods. In changing climatic situations, metabolism and physiological responses also change and require elevated demand for energy intake through food, and therefore, a nutritional strategy should be developed to address this phenomenon. Accordingly, nutritional bioenergetic models have been devised with the determination of optimal protein and energy requirements under different temperature regimes for several fish species, such as rainbow trout *Oncorhynchus mykiss* (Hua and Bureau 2009), Nile tilapia *Oreochromis niloticus* (Chowdhury et al. 2013), and Asian seabass *Lates calcarifer* (Glencross and Bermudes 2012). Feed quality may also influence the adaptive response to climatic stressors. Dietary supplementation of grape seed extract having antioxidant properties and sea lettuce *Ulva lactuca* improved survival of the greenlip abalone *Haliotis laevigata* at high-temperature conditions (Lange et al. 2014). It was demonstrated that dietary manipulation of the mineral Mg:Ca ratio could ameliorate coping capacity to acidification in the purple sea urchin *Paracentrotus lividus* (Asnaghi et al. 2014). As an adaptive strategy to increase temperature in mirror carp *Cyprinus carpio*, immune response, antioxidant enzymes, and heat shock protein gene expression were elevated by incorporation of higher dietary protein level (Huang et al. 2015). Stress due to low temperature can be ameliorated by an antioxidant product from the honeybee, propolis in seabass (Šegvić-Bubić et al. 2013). Dietary immunostimulants may provide protective effects under the climate change conditions in fish (Wang et al. 2017).

3.2 Sourcing of Diets and Feeding Management

Expansion of aquaculture globally may not inevitably be affected by the decline in capture fisheries which may or may not be climate-driven. The World Bank and the FAO predicted that a steady increase in the price of fishmeal as one of the important feed ingredients will necessitate the exploration of alternative feedstuffs with technological advances that ensure the aquaculture growth sustained (World Bank 2013). It is evident that herbivorous and omnivorous species, such as carps, tilapia, shrimp, and catfish remain to be the major aquaculture species consuming commercial feeds (Tacon and Metian 2015). These species have flexible feeding habits that provide wider opportunities for utilization of alternative and unconventional feedstuffs compared to carnivorous species (Olsen and Hasan 2012). Several mariculture species in China, Indonesia, Taiwan, Malaysia, and Thailand are fed completely with low-value trash fish which gives rise to low feed conversion efficiency (FAO 2014). On the contrary, low-value fish as a feed ingredient could provide good feed conversion efficiency in some farming systems (Bunlipatanon et al. 2014), indicating the possibility of effective utilization of this feedstuff. At the same time, FAO (2014) implied that shifting to the use of compound feeds would certainly increase feed efficiency and reduce the dependence on the fish-based ingredients to a great extent rather than the use of the feed containing low-value trash fish. World aquaculture will continue to expand with reduced reliance on fishmeal usage (Olsen and Hasan 2012), as there has been successful farming of carnivorous species fed with low fish-origin ingredients. In the case of Atlantic salmon, the requirement of marine protein to produce 1 kg of fish flesh could be reduced significantly to 0.7 kg, which will surely reduce the dependence on marine protein (Ytrestøyl et al. 2015).

Dealing the hardship in aquaculture nutrition in the changing climatic situations can be efficiently achieved by adopting various sourcing strategies for nutrients. These strategies can include locally available nutritionally balanced feed ingredients (Tacon et al. 2011) and the utilization of alternative climate-resilient crops with desirable nutritional properties (Hall 2015). Although utilization of crop-based ingredients for aquaculture feed may reduce some pressure on marine resources, climate change effect could give rise to increased food demand (Fry et al. 2016) with a projection of inadequate food grain production for global demand by 2050 (Ray et al. 2013; Asseng et al. 2015). Furthermore, the use of crop-based ingredients in aquafeeds may pose unfavorable consequences to human health as the land-based feedstuffs contain a low level of omega-3 FA (Fry et al. 2016). As the omega-3 FA sources from marine supplies may turn out to be insufficient, new and novel sources of omega-3 FA are required to be searched, and it is a subject of current research in aquaculture nutrition (Tocher 2015).

The species which obtain their diet from surrounding environment could face both challenges and opportunities during the climate adversities. There will be a greater challenge for the environmental extractive species, such as shellfish and seaweeds, as the climate change may straightway alter the quality and quantity of available nutrition to them. Therefore, a change of farm location could be an effective strategy (Soto et al. 2018). More control on the feeding of extractive species could be achieved through land-based aquaculture systems, but at the same time, this may involve higher expenditure for other facilities, such as infrastructure, land, and machinery.

3.3 Climate Adaptive Farming Systems with the Intrinsic Nutritional Management Approach

Diversification of farming systems can be a climate-resilient and effective approach. Integrated aquaculture systems that utilize intrinsic nutrients will be more climate adaptive. In this direction, rice-fish farming methods and integrated multi-trophic aquaculture (IMTA) are recommended for climate change adaptation (Binh et al. 2017). The rice-fish farming system is an ecologically efficient approach that improves soil fertility and water quality through the release of N and P along with control of pests by fish, thus use of fertilizers and pesticides gets reduced (Halwart and Gupta 2004). IMTA is an ecosystem-based concept that involves two or more aquatic species from different trophic levels in a single production unit as a viable substitute to transform aquaculture more profitable and sustainable (Chopin et al. 2001; Muangkeow et al. 2007; Zimmermann and New 2000). The waste of main cultured species or fed species (finfish) is utilized by unfed or auxiliary species called extractive species, categorized as organic extractive (shellfish) and inorganic extractive (microalgae) species, as their energy or nutrient source and growth (Biswas et al. 2019, 2020). IMTA utilizes organic solid wastes and inorganic dissolved nutrients by converting them into diets of cultured species (Chopin et al. 2012; Reid et al. 2013). Thus, it is a more nutrient-efficient system compared to conventional aquaculture systems. Integrated aquaculture systems are a suitable approach as a strategy for climate adaptation because there will be surely the production of at least one crop when others may fail (Chopin et al. 2012; Oyebola and Olatunde 2019). Through an integrated aquaculture approach, two purposes can be attained, diversity in culture systems and elevated utilization of nutrients, moreover, there will be the improvement of water quality (IFAD 2014; Shelton 2014; Oyebola and Olatunde 2019). Another climate-resilient approach that requires minimal use of feed and management for wild self-recruiting fish stock (Beveridge et al. 2018) is culture-based capture fisheries which are based on the principle of stocking and recapturing of fish (De Silva 2016; Oyebola and Olatunde 2019). This practice has the potential of future expansion in countries with the scarcity of space and resources.

4 Conclusion

Overall, the effects of climate change on aquaculture may be challenging and detrimental. However, developing and finding the dealing strategies will encourage and help the stakeholders. So far, several aquaculture adaptation strategies to climate change, ranging from easy approaches to complex technical solutions have been suggested. In this regard, the management of the nutrition and feeding of aquaculture animals will be a hard task. The availability and future status of aquaculture feed resources and their utilization should be analyzed from a global perspective considering the potential impacts of climate change hardship. It is predicted that fish production will be affected by climate adversities with their impacts on the sourcing of ingredients and the production of feed. However, the global demand for feedstuffs will rely on the level of intensification of aquaculture systems for enhanced production per unit. Keeping attention to the aquaculture production will address the issues related to dealing strategies that include adaptive and extenuation measures of climate change with regard to sourcing of feed, feeding management, and use of natural resources, such as land and water. Although, aquaculture is playing a pivotal role in the livelihood and socio-economic situation of small and marginal producers in the developing regions, several issues related to nutritional management remain unaddressed. Issues on actual feed requirement, demand, and supply for aquaculture in climate change situations are poorly studied. Globally, climate change variables and data are being recorded continuously and these changing situations would have strong impacts on the nutritional and food security through aquaculture. Adaptive measures have to be developed by government sectors, as well as aquaculture stakeholders to efficiently deal the environmental changes. However, long-term measures for climate change should be the prime focus that addresses the deleterious consequences of anthropogenic activities.

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References

Acevedo-Trejos E, Brandt G, Steinacher M et al (2014) A glimpse into the future composition of marine phytoplankton communities. Front Mar Sci 1:15. https://doi.org/10.3389/fmars.2014.00015

Allison EH, Beveridge MCM, van Brakel M (2009) Climate change, small-scale fisheries and smallholder aquaculture. In: Wramner P, Cullberg M, Ackefors H (eds) Fisheries, sustainability and development. Royal Swedish Academy of Agriculture and Forestry, Stockholm, pp 103–122

Asnaghi V, Mangialajo L, Gattuso JP et al (2014) Effects of ocean acidification and diet on thickness and carbonate elemental composition of the test of juvenile sea urchins. Mar Environ Res 93:78–84. https://doi.org/10.1016/j.marenvres.2013.08.005

Asseng S, Ewert F, Martre P et al (2015) Rising temperatures reduce global wheat production. Nat Clim Chang 5:143–147. https://doi.org/10.1038/nclimate2470

Beveridge MCM, Dabbadie L, Soto D et al (2018) Climate change and aquaculture: interactions with fisheries and agriculture. In: Barange M, Bahri T, Beveridge MCM, Cochrane KL, Funge-Smith S, Poulain F (eds) Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. Fish Aquacult Tech Pap 627. FAO, Rome, pp 491–500

Binh MN, Van An L, Thuy NTT et al (2017) Impact of climate change on aquaculture in Phu Vang District, Thua Thien Hue Province, Vietnam. In: Agriculture and development discussion paper series 2017–3. Southeast Asian regional Center for Graduate Study and Research in agriculture (SEARCA), Los Baños

Biswas G, Kumar P, Kailasam K et al (2019) Application of integrated multi-trophic aquaculture (IMTA) concept in brackishwater eco-system: the first exploratory trial in the Sundarbans, India. J Coast Res SI 86:49–55. https://doi.org/10.2112/SI86-007.1

Biswas G, Kumar P, Ghoshal TK et al (2020) Integrated multi-trophic aquaculture (IMTA) outperforms conventional polyculture with respect to environmental remediation, productivity and economic return in brackishwater ponds. Aquaculture 516:734626. https://doi.org/10.1016/j.aquaculture.2019.734626

Brander KM (2007) Global fish production and climate change. Proc Natl Acad Sci U S A 104: 19709–19714. https://doi.org/10.1073/pnas.0702059104

Brugère C (2015) Climate change vulnerability in fisheries and aquaculture: a synthesis of six regional studies. In: FAO fisheries circular. FAO, Rome

Brummett RE, Beveridge MCM (2016) Aquaculture. In: Craig JF (ed) Freshwater fisheries ecology. Wiley Blackwell, New York

Buchheister A, Miller TJ, Houde ED et al (2016) Spatial and temporal dynamics of Atlantic menhaden (*Brevoortia tyrannus*) recruitment in the Northwest Atlantic Ocean. ICES J Mar Sci 73:1147–1159. https://doi.org/10.1093/icesjms/fsv260

Bunlipatanon P, Songseechan N, Kongkeo H et al (2014) Comparative efficacy of trash fish versus compounded commercial feeds in cage aquaculture of Asian seabass (*Lates calcarifer*) (Bloch) and tiger grouper (*Epinephelus fuscoguttatus*) (Forsskål). Aquacult Res 45:373–388. https://doi.org/10.1111/j.1365-2109.2012.03234.x

Chopin T, Buschmann AH, Halling C et al (2001) Integrating seaweeds into marine aquaculture systems: a key toward sustainability. J Phycol 37:975–986. https://doi.org/10.1046/j.1529-8817.2001.01137.x

Chopin T, Cooper JA, Reid G et al (2012) Open-water integrated multi-trophic aquaculture: environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture. Rev Aquacult 4:209–220. https://doi.org/10.1111/j.1753-5131.2012.01074.x

Chowdhury MAK, Siddiqui S, Hua K et al (2013) Bioenergetics-based factorial model to determine feed requirement and waste output of tilapia produced under commercial conditions. Aquaculture 410–411:138–147. https://doi.org/10.1016/j.aquaculture.2013.06.030

Cinner JE, Adger WN, Allison EH et al (2018) Building adaptive capacity to climate change in tropical coastal communities. Nat Clim Chang 8:117–123. https://doi.org/10.1038/s41558-017-0065-x

De Silva SS (2016) Culture based fisheries in Asia are a strategy to augment food security. Food Secur 8:585–596. https://doi.org/10.1007/s12571-016-0568-8

De Silva SS, Soto D (2009) Climate change and aquaculture: potential impacts, adaptation and mitigation. In: Cochrane K, De Young C, Soto D et al (eds) Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper No. 530, Rome, pp 151–212

Doney SC (2006) Plankton in a warmer world. Nature 444:695–696. https://doi.org/10.1038/444695a

FAO (2014) The state of world fisheries and aquaculture: opportunities and challenges. Reproduction 1020–5489. FAO, Rome

Fitzgerald-Dehoog L, Browning J, Allen BJ (2012) Food and heat stress in the California mussel: evidence for an energetic trade-off between survival and growth. Biol Bull 223:205–216. https://doi.org/10.1086/BBLv223n2p205

Fry JP, Love DC, MacDonald GK et al (2016) Environmental health impacts of feeding crops to farmed fish. Environ Int 91:201–214. https://doi.org/10.1016/j.envint.2016.02.022

Glencross BD, Bermudes M (2012) Adapting bioenergetic factorial modelling to understand the implications of heat stress on barramundi (*Lates calcarifer*) growth, feed utilisation and optimal protein and energy requirements—potential strategies for dealing with climate change? Aquacult Nutr 18:411–422. https://doi.org/10.1111/j.1365-2095.2011.00913.x

Hall GM (2015) Impact of climate change on aquaculture: the need for alternative feed components. Turk J Fish Aquat Sci 15:569–574. https://doi.org/10.4194/1303-2712-v15_2_45

Hall SJ, Delaporte A, Phillips MJ et al (2011) Blue Frontiers: managing the environmental costs of aquaculture. World Fish Center, Penang, Malaysia

Hallegraeff GM (2010) Ocean climate change, phytoplankton community responses, and harmful algal blooms: a formidable predictive challenge. J Phycol 46:220–235. https://doi.org/10.1111/j.1529-8817.2010.00815.x

Halwart M, Gupta MV (2004) Culture of fish in rice fields. Food and Agriculture Organization of the United Nations and the WorldFish Center, Penang, Malaysia

Hanjra MA, Qureshi ME (2010) Global water crisis and future food security in an era of climate change. Food Policy 35:365–377. https://doi.org/10.1016/j.foodpol.2010.05.006

Hixson SM, Arts MT (2016) Climate warming is predicted to reduce omega-3, long-chain, polyunsaturated fatty acid production in phytoplankton. Glob Chang Biol 22:2744–2755. https://doi.org/10.1111/gcb.13295

Hua K, Bureau DP (2009) Development of a model to estimate digestible lipid content of salmonid fish feeds. Aquaculture 286:271–276. https://doi.org/10.1016/j.aquaculture.2008.09.028

Huang JF, Xu QY, Chang YM (2015) Effects of temperature and dietary protein on gene expression of *Hsp70* and *Wap65* and immunity of juvenile mirror carp (*Cyprinus carpio*). Aquacult Res 46: 2776–2788. https://doi.org/10.1111/are.12432

IFAD (International Fund for Agricultural Development) (2014) Guidelines for integrating climate change adaptation into fisheries and aquaculture projects. https://www.ifad.org/documents/38714170/39135645/fisheries.pdf

Lange B, Currie KL, Howarth GS et al (2014) Grape seed extract and dried macroalgae, *Ulva lactuca* Linnaeus, improve survival of greenlip abalone, *Haliotis laevigata* Donovan, at high water temperature. Aquaculture 433:348–360. https://doi.org/10.1016/j.aquaculture.2014.06.028

Lindegren M, Checkley DM, Rouyer T et al (2013) Climate, fishing, and fluctuations of sardine and anchovy in the California current. Proc Natl Acad Sci U S A 110:13672–13677. https://doi.org/10.1073/pnas.1305733110

Melzner F, Stange P, Trübenbach K et al (2011) Food supply and seawater *p*CO2 impact calcification and internal shell dissolution in the blue mussel *Mytilus edulis*. PLoS One 6:e24223. https://doi.org/10.1371/journal.pone.0024223

Merino G, Barange M, Mullon C (2010) Climate variability and change scenarios for a marine commodity: modelling small pelagic fish, fisheries and fishmeal in a globalized market. J Mar Syst 81:196–205. https://doi.org/10.1016/j.jmarsys.2009.12.010

Muangkeow B, Ikejima K, Powtongsook S et al (2007) Effects of white shrimp, *Litopenaeus vannamei* (Boone), and Nile tilapia, *Oreochromis niloticus* L., stocking density on growth, nutrient conversion rate and economic return in integrated closed recirculation system. Aquaculture 269:363–376. https://doi.org/10.1016/j.aquaculture.2007.04.002

Olsen RL, Hasan MR (2012) A limited supply of fishmeal: impact on future increases in global aquaculture production. Trends Food Sci Technol 27:120–128. https://doi.org/10.1016/j.tifs.2012.06.003

Oyebola OO, Olatunde OM (2019) Climate change adaptation through aquaculture: ecological considerations and regulatory requirements for tropical Africa. In: Bamutaze Y, Kyamanywa S, Singh BR, Nabanoga G, Lal R (eds) Agriculture and ecosystem resilience in sub Saharan Africa. Springer, Cham, pp 435–472

Parker LM, Ross PM, O'Connor WA et al (2013) Predicting the response of molluscs to the impact of ocean acidification. Biol 2:651–692. https://doi.org/10.3390/biology2020651

Ray DK, Mueller ND, West PC et al (2013) Yield trends are insufficient to double global crop production by 2050. PLoS One 8:e66428. https://doi.org/10.1371/journal.pone.0066428

Raza A, Razzaq A, Mehmood SS et al (2019) Impact of climate change on crops adaptation and strategies to tackle its outcome: a review. Plan Theory 8:34. https://doi.org/10.3390/plants8020034

Reid GK, Chopin T, Robinson SMC et al (2013) Weight ratios of the kelps, *Alaria esculenta* and *Saccharina latissima*, required to sequester dissolved inorganic nutrients and supply oxygen for Atlantic salmon, *Salmo salar*, in integrated multi-trophic aquaculture systems. Aquaculture 408-409:34–46. https://doi.org/10.1016/j.aquaculture.2013.05.004

Reid GK, Gurney-Smith HJ, Flaherty M et al (2019) Climate change and aquaculture: considering adaptation potential. Aquac Environ Interact 11:603–624. https://doi.org/10.3354/aei00333

Richards RG, Davidson AT, Meynecke JO et al (2015) Effects and mitigations of ocean acidification on wild and aquaculture scallop and prawn fisheries in Queensland, Australia. Fish Res 161: 42–56. https://doi.org/10.1016/j.fishres.2014.06.013

Šegvić-Bubić T, Boban J, Grubišić L et al (2013) Effects of propolis enriched diet on growth performance and plasma biochemical parameters of juvenile European sea bass (*Dicentrarchus labrax* L.) under acute low temperature stress. Aquacult Nutr 19:877–885. https://doi.org/10.1111/anu.12032

Shelton C (2014) Climate change adaptation in fisheries and aquaculture-compilation of initial examples. In: FAO fisheries and aquaculture circular no. 1088. FAO, Rome

Soto D, Ross LG, Handisyde N et al (2018) Climate change and aquaculture: vulnerability and adaptation options. In: Barange M, Bahri T, Beveridge MCM, Cochrane KL, Funge-Smith S, Poulain F (eds) Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. Fish Aquacult Tech Pap 627. FAO, Rome, pp 465–490

Tacon AGJ, Metian M (2015) Feed matters: satisfying the feed demand of aquaculture. Rev Fish Sci Aquacult 23:1–10. https://doi.org/10.1080/23308249.2014.987209

Tacon AGJ, Hasan MR, Metian M (2011) Demand and supply of feed ingredients for farmed fish and crustaceans: trends and prospects. In: FAO Fish Aquacult Tech Pap 564. FAO, Rome

Thomsen J, Casties I, Pansch C et al (2013) Food availability outweighs ocean acidification effects in juvenile *Mytilus edulis*: laboratory and field experiments. Glob Chang Biol 19:1017–1027. https://doi.org/10.1111/gcb.12109

Timmins-Schiffman E, O'Donnell M, Friedman C et al (2013) Elevated pCO_2 causes developmental delay in early larval Pacific oysters, *Crassostrea gigas*. Mar Biol 160:1973–1982. https://doi.org/10.1007/s00227-012-2055-x

Tocher DR (2015) Omega-3 long-chain polyunsaturated fatty acids and aquaculture in perspective. Aquaculture 449:94–107. https://doi.org/10.1016/j.aquaculture.2015.01.010

Turral H, Burke J, Faurés J-M (2011) Climate change, water and food security. Food and Agriculture Organization of the United Nations, Rome

Vosloo D, van Rensburg L, Vosloo A (2013) Oxidative stress in abalone: the role of temperature, oxygen and L-proline supplementation. Aquaculture 416–417:265–271. https://doi.org/10.1016/j.aquaculture.2013.09.031

Wang W, Sun J, Liu C et al (2017) Application of immunostimulants in aquaculture: current knowledge and future perspectives. Aquacult Res 48:1–23. https://doi.org/10.1111/are.13161

Wikfors GH, Ohno M (2001) Impact of algal research in aquaculture. J Phycol 37:968–974. https://doi.org/10.1046/j.1529-8817.2001.01136.x

World Bank (2013) Fish to 2030: prospects for fisheries and aquaculture. Rep 83177-GLB. World Bank, Washington, DC

WRI (World Resources Institute) (2014) Increasing productivity of aquaculture. Working paper, Installment 6 of creating a sustainable food future. World Resources Institute, Washington, DC

Ytrestøyl T, Aas TS, Åsgård T (2015) Utilisation of feed resources in production of Atlantic salmon (*Salmo salar*) in Norway. Aquaculture 448:365–374. https://doi.org/10.1016/j.aquaculture.2015.06.023

Zimmermann S, New MB (2000) Grow-out systems polyculture and integrated culture. In: New MB, Valenti WC (eds) Freshwater prawn farming: the farming of *Macrobrachium rosenbergii*. Blackwell Science, London, pp 187–202

Strategies to Mitigate Climate Change-Imposed Challenges in Fish Nutrition

F. J. Fawole and Shamna Nazeemashahul

Abstract

Climate change is not only a future threat to food security but also a present reality that has its signature in all aspects of sustainability. The changes in climate and global warming have potential short-term and long-term effects on aquaculture production. Changes in the ecosystem, especially variations in temperature, can alter the physiology of fish and create stress in animals. Mitigation of stress in fish and crustacea can be done through nutritional interventions. Functional feed additives or nutraceuticals play a major role in the mitigation of stress in fish. The improved tolerance and feed conversion efficiency can also support the fish to cope with climate- related challenges. Additionally, providing a precise, eco-friendly feed that stimulates gut health, growth, and immunity in fish can be a better strategy to support the growth and well-being of fish in the changing climatic conditions.

Keywords

Precision nutrition · Nutraceuticals · Climate change mitigation · Gut health · Stressors in aquaculture

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Abbreviations

AI	Artificial intelligence
ALT	Alanine aminotransferase
AST	Aspartate aminotransferase
CAT	Catalase
FCE	Feed conversion efficiency
GAS	General adaptive syndrome
IMTA	Integrated multitrophic aquaculture
IoT	Internet of Things
LDH	Lactate dehydrogenase
MDH	Malate dehydrogenase
SNPs	Single nucleotide polymorphisms
SOD	Superoxide dismutase

1 Introduction

An increase in temperature can have a positive effect on metabolism to a certain extent, beyond which it will have an adverse effect (Jobling 1995). Climate change may alter reproductive and migratory patterns, age at first maturity, fecundity, growth, survival, etc. (Crozier and Hutchings 2014). To improve the production from aquaculture, feeding plays a major role, and the energy available from the feed will be used for growth and maintenance. The changes in normal physiology may result in changes in feed intake, metabolism, and feed utilization. There are several foods or food-derived particles that play a role in mitigating the stress responses in fish (Ciji and Akhtar 2021). Understanding the nutritional requirements and including nutraceuticals or functional additives improves nutrient utilization and mitigates the long-term effects of climate change and global warming. Furthermore, feeding an appropriate amount of nutrients at optimum levels and enhancing their maximum utilization through various feeding strategies can support adaptation and mitigation to climate change in fish. In addition, the development of species-specific eco-friendly feeds would not only improve the growth of the fish but also ensure sustainability.

2 Stressors and Other Challenges in AquaCulture Systems

2.1 Stressors in Aquaculture Systems

Climate change and the effects of global warming are now being felt throughout the world, with attendant changes in the climate pattern. This has caused an increase in the incidence of extreme weather events such as flooding, droughts, intense

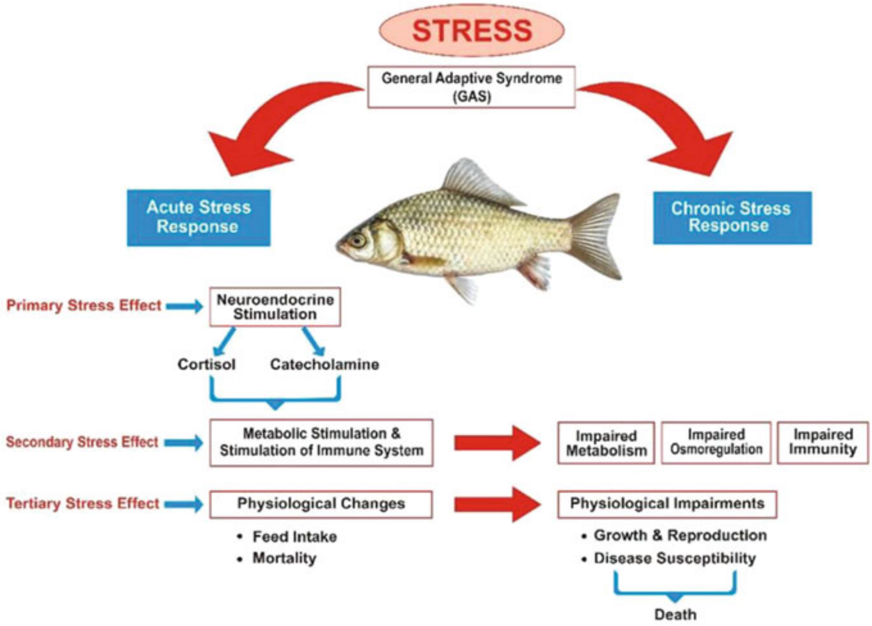

Fig. 1 Stress response and impacts on fish

precipitation, increased water temperatures, and ecological drifts. Fish, being a poikilothermic animal can easily be affected by changes in temperature. An increase or decrease in water temperature can cause hydrological stress and cause changes in water quality (Nowicki et al. 2019). Also, an increase in temperature can decrease the oxygen levels in the aquatic medium, which can cause hypoxic stress. Furthermore, temperature fluctuations can stifle the growth of natural food organisms, especially plankton, resulting in diet restriction and starvation. These stressors can cause oxidative stress at the cellular level and could result in an imbalance in the antioxidant system of fish. All these stressors can induce acute and chronic stress responses in fish, which are otherwise called "General Adaptive Syndrome (GAS)" (Fig. 1). They can result in reduced feed intake, impaired digestion, metabolism, and absorption, weakening of the immune and antioxidant systems, and reducing the overall growth of fish. Weakened immunity can lead to an easy outbreak of the disease in the system.

2.2 Physiological Changes in Response to Stressors

Extreme temperature (hot and cold) occurrences caused by climate change are threatening a wide range of fish species, ecosystems, and aquaculture systems (Islam et al. 2021). Fluctuations in temperature affect all biochemical and physiological activities of fish, including growth, feed intake, reproduction, survival, behavior, and distribution (Debnath et al. 2006; Islam et al. 2021). Changing the energetic cost of physiological homeostasis, osmotic, and ionic regulation has been reported to cause high mortality of fish during winter and summer extremes (Pörtner and Peck 2010; Madeira et al. 2016; Shen et al. 2018; Shrivastava et al. 2017). Although the increase in temperature is expected to disrupt fish homeostasis and cause physiological stress in aquatic species, temperature changes do exhibit some positive effects. An increase in temperature up to a certain level has been shown to benefit aquaculture by increasing growth rates and food conversion efficiency. For instance, Das et al. (2005) revealed that the temperature for growth and improved feed efficiency for *Labeo rohita* was in the range of 31–33 °C, which was higher than the earlier reported range of 24 °C—26 °C (Kausar and Salim 2006). However, exceeding a species' optimal temperature range has a negative impact on aquatic animal health due to metabolic stress, which increases oxygen demand and disease susceptibility (Manush et al. 2004). Furthermore, ambient water temperature influences the development of innate and acquired immunity in fish, and elevated water temperatures have been reported to cause a reduction in white blood cells, total protein, albumin, and globulin in *Cyprinus carpio* and *Tor putitora* (Verma et al. 2007; Akhtar et al. 2013a, b).

3 Mitigation Measures

Climate change has undoubtedly had a direct impact on the nutrition and physiology of fishes, potentially reducing fish performance and impairing health conditions. Therefore, to reduce the resultant negative effect of this global warming on cultured fish, a nutritional intervention-based mitigation strategy is critical to ensure sustainable aquaculture. One effective strategy to accomplish this includes the use of immunoceuticals, antioxidants, and antistress compounds. Another important strategy will be integrated aquaculture systems that explore the various niches effectively. Changes in climate may result in changes in agricultural cropping patterns and fish stock shifting. This may create a shortage in the availability of ingredients on time and in sufficient quantity. The shortage of ingredients can be rectified by exploring the use of locally available seasonal ingredients such as leafmeal, fruits, vegetable waste, etc. In addition to this, the increase in the production of insect meals and other invertebrate meals will be a replacement for many of the conventional protein sources. Understanding the nutritional requirements and precision farming will be another major solution to cope with the effects of climate change on fish nutrition. Feeding the required nutrients at the optimal level in a precise quantity will increase the utilization of the feed efficiently, thereby reducing wastage. This can ensure reduced excretion of nitrogen and organic matter into the system, which may reduce eutrophication and pollution. Species selection and stock identification based on feed conversion efficiency (FCE), thermal tolerance, hypoxia tolerance, or another related adaptability will be another important strategy. The genetically improved fishes can cope with the environmental changes very quickly and get acclimatized to them more efficiently than their counterparts.

3.1 Efficacy of Dietary Immunoceuticals in Mitigating Temperature-Related Stress in Fish

Immunoceuticals, which are naturally occurring compounds, are substances that have immunotherapeutic efficacy when taken orally (Kidd 2000). One of the ways of achieving the concept of immunoceuticals is by dietary supplementation of immunostimulants, which are classified as functional feed additives (Dawood et al. 2018). In fish, immunostimulants have been reported to have the ability to activate defense systems even in stressful conditions, thus reversing the adverse effects mediated by stressors (Ortuno et al. 2003; Sarma et al. 2009; Akhtar et al. 2012; Shamna et al. 2020, 2021). Several dietary supplements like glucans, mannan oligosaccharides, vitamin C, propolis, astaxanthin, tryptophan, etc. have been examined for their ability to protect fish from extreme temperature-related stressors and enhance the fish immune response. For example, dietary astaxanthin supplementation improved growth performance, elevated the activities of hepatic superoxide dismutase and catalase enzymes, and induced HSP70 in pufferfish (*Takifugu obscurus*) maintained at high temperature (Cheng et al. 2018). The study found that feeding astaxanthin to fish increased their growth and immunological response and enhanced the antioxidant activity. Similarly, there was an indication that propolis (3—4 g/kg diet) extract supplementation improved the growth performance, feed utilization efficiency, and enhanced the resistance of Nile tilapia to cold temperature stress (Hassaan et al. 2019). The reason for the enhanced performance could be associated with the high concentration of vitamins (B1, C, and E) and minerals (iron, manganese, aluminum, and silicon) present in propolis and their roles as cofactors in digestive and enzymatic activity. Stress mitigation has also been studied in *L. rohita* fingerlings reared under thermal stress, and the results show that L-tryptophan supplementation alleviates thermal stress, boosts growth, and modulates immunity in *L. rohita* fingerlings (Akhtar et al. 2013a, b; Kumar et al. 2014). Gilthead seabream fed a winter feed supplemented with vitamin C, E, choline, taurine, phospholipid, and polyunsaturated fatty acids have been reported to show an improved immune response upon cold temperature stress (Tort et al. 2004; Schrama et al. 2017). Furthermore, diets rich in polyunsaturated fatty acids and less in saturated fatty acids such as sunflower or linseed oils could improve the growth performance of Nile tilapia, *Oreochromis niloticus*, during cold thermal stress (Corrêa et al. 2017, 2018).

Extreme weather events, such as high or low temperatures that exceed the optimum limits of a particular species, can be stressful for fish and have a negative impact on the health of aquatic animals due to increased oxygen demand and metabolic stress. This could result in physiological and behavioral adaptations to cope with temperature fluctuations. Such adaptive responses may occur instantaneously or gradually after a period of acclimation. Biochemical adaptations could be measured by changes in metabolic enzyme activity, changes in the lipid composition of cellular membranes, or quantitative changes in total or specific proteins. Thermal stress increases the hepatic and muscle enzyme activities of aspartate aminotransferase (AST) and alanine aminotransferase (ALT) in *Labeo rohita* exposed to a higher temperature (34–36 °C). The higher activity of AST and ALT indicates the mobilization of aspartate and alanine via gluconeogenesis for glucose production to cope with stress (Kumar et al. 2014). Nevertheless, the effect of thermal stress was, however, reversed with the supplementation of dietary L-tryptophan. It was observed that the addition of 1.42% tryptophan resulted in a drastic reduction in the activity of both transferases and, this implies that L-tryptophan could mitigate the adverse effect of thermal stress in *L. rohita*. Such inclusion was also found effective in lowering the activity of lactate dehydrogenase (LDH) and malate dehydrogenase (MDH) in *L. rohita* after exposure to thermal stress (34–36 °C) but was higher in the group that was not fed dietary L-tryptophan. Studies have shown that pyridoxine plays a vital role in stimulating the immune response of *L. rohita* fingerlings exposed to elevated temperatures by increasing white blood cells, respiratory burst and lysozyme activity, serum albumin, and globulin (Ahktar et al. 2012). The authors suggested that supplementing with 100 mg of pyridoxine per kg diet could reverse the negative effects of high temperatures and protect the fish in water temperatures as high as 33 °C.

3.2 Efficacy of Dietary Antioxidants and Antistress Compounds in Mitigating Thermal-Induced Stress and Immune Suppression in Fish

The use of immunoceuticals as antioxidants and antistress agents is relatively new, and much research is being conducted in this area. The addition of vitamin C and iron nanoparticles at 6 g/kg and 4 g/kg, respectively, was found adequate as a stress-reducing agent for African catfish, *Clarias gariepinus,* during hyperthermia stress. After being exposed to thermal-induced stress, vitamin C and iron nanoparticles caused a decrease in the release of glucose, a physiological stress biomarker, into the bloodstream of the fish. Similarly, feeding vitamin C to hybrid grouper reared under acute low temperature stress resulted in a reduction in cortisol levels compared to the higher concentration recorded in the control (Hao et al. 2017). This beneficial effect could be due to vitamin C's antioxidative capability in regulating the release of the stress hormone cortisol, which could stimulate hepatic gluconeogenesis and increase glucose production during stress. Cortisol is known to regulate glucose mobilization through cortisol-dependent enhancement of gluconeogenesis, and an elevated level of cortisol in the blood is considered an indicator of stress (Vijayan et al. 1997; Wendelaar Bonga 1997). Interestingly, the addition of propolis extract at 4 g/kg was found to significantly reduce glucose and cortisol levels in Nile tilapia reared under cold stress (Hassaan et al. 2019). Similarly, 2.5 g/kg of propolis is reportedly enough to inhibit oxidative stress in seabass subjected to short-term cold stress (Šegvić-Bubić et al. 2013).

During the thermal stress condition in fish, reactive oxygen species (ROS) are released, and when these ROS accumulate, it can trigger cell damage when there is an imbalance between ROS production and the antioxidant enzyme system. This was evidenced in pufferfish (*Takifugu obscurus*), where higher ROS production was detected in fish exposed to high thermal stress. However, feeding astaxanthin to the fish helped reduce the level of ROS more than those of the control group (unsupplemented group), and this mitigation effect was based on the antioxidant capacity of astaxanthin in scavenging excess ROS produced (Cheng et al. 2018). Moreover, the superoxide dismutase (SOD) and catalase (CAT) enzyme activities were found to be higher in response to ROS production. It is worthy of note that the fish fed astaxanthin had the highest activity, and this points to the antioxidant potency of astaxanthin in protecting fish against thermal-induced oxidative stress. Pyridoxine supplementation has also been shown to improve growth performance, as well as the activity of various antioxidant enzymes and stress indicators in *L. rohita* subjected to elevated temperatures (Akhtar et al. 2012).

It appears that immunoceuticals, antioxidants, and antistress agents seem to be promising nutritional strategies to attenuate thermal stress effects, and this could have positive implications for sustainable aquaculture.

3.3 Maintaining Gut Health

The gastrointestinal tract is a complex system with a fluctuating number of microbial units and the interactions between these microbial communities and the host play a crucial role in deciding the growth and well-being of fish (Lee and Mazmanian 2014). The health of the gut determines the digestive process, absorption, metabolic regulations, and other related bodily functions. The signals between a healthy gut and brain help in maintaining growth and health, and the gut microbes have a definite role in it (Perry et al. 2020). Currently, there are a few attempts to understand the interaction between microbes and the host immune system (Kelly and Salinas 2017), physiology (Yukgehnaish et al. 2020), and energy balancing (Butt and Volkoff 2019) and observed that the gut health heavily depends on changes in environment like water, diet, temperature, salinity, etc. (Ye et al. 2011; Butt and Volkoff 2019). Studies showed that the gut microbiome controls more than 212 genes related to various bodily functions including digestion, absorption, and metabolism in fish (Wang et al. 2018). In addition to proteases, carbohydrases, and lipases, the fish gut microbiome produces a series of other digestive enzymes like cellulase, chitinase, phosphatases, etc. which can enhance digestibility (Ray et al. 2012; Wu et al. 2015). Similarly, the anaerobic fermentation by various bacteria can provide energy and several metabolites like short-chain fatty acids, amino acids, vitamin B12 (observed in tilapia), etc. Changes in climatic condition may affect the cropping patterns, shift the fish stocks, and result in the non-availability of many ingredients. Recent research revealed that the unconventional ingredients have an influence on gut microbiota, for example, the insect meals rich in chitin have a prebiotic role and support gut health and immunity (Huyben et al. 2019; Hoseinifar et al. 2019, and Miao et al. 2018). *Pseudomonas* sp. and *Lactobacillus* are common species observed in insect meal fed groups (Bruni et al. 2018).

The stress associated with climate change and global warming may result in hypoxia and related starvation in fish. This can change the composition of microbiota in fish. For example, the *beta proteobacteria* are replaced by *Bacteroidetes* in the gut of 8-day starved Asian seabass (Xia et al. 2014) and such changes have long-term implications.

3.4 Integrated or Less Fed Aquaculture

Climate-smart aquaculture systems, along with feed and feeding management, can also compensate for the pressure of climate variation on fish. The biofloc and IMTA (integrated multitrophic aquaculture) systems facilitate less feed input into the system as the natural food available in the system will meet half of the nutritional needs of cultured fish. That can reduce the associated waste generation, put less pressure on the environment, and support the sustainability of aquaculture.

3.5 Alternate Ingredients

Sustainable aquaculture production depends on eco-friendly and lower carbon footprint feeds. Significant efforts have been made to replace fishmeal with eco-friendly ingredients like insect meal, single-cell proteins, algae, and other terrestrial plant-based ingredients. Designing efficient tools for precise feed production requires nutritional data on potential eco-friendly ingredients, particularly their life cycles. Similarly, the toxic compounds, anti-nutrients, and digestibility of these ingredients need to be studied and documented. To meet the ingredient non-availability, utilization of organic wastes like fruits and vegetable wastes will be a potential strategy. This will reduce the pressure on the ecosystem to degrade the tons of organic waste generated. The utilization of nonedible seeds or their by-products will be another important strategy. Most of these nonedible seeds are rich in protein (Table 1) and extraction of that protein in the form of protein concentrate or isolate can remove the anti-nutrients in it (Shamna et al. 2015, 2017; Fawole et al. 2018; Jayant et al. 2021). Leaves contribute a major chunk of organic waste, and the utilization of leafmeal to replace conventional ingredients like rice bran will be another potential option.

Table 1 Crude protein anti-nutritional factors of oilcake and protein isolates of nonedible oilseed

Nonedible seed	Oilcake (%)	Protein concentrate/isolate (%)	References
Jatropha seed	27–33	87.00	Shamna et al. (2015)
Cotton seed	38–44	72.20	Gerasimidis et al. (2007)
Rubber seed	22–25	90.80	Fawole et al. (2016)
Neem seed	23.45	82.04	Gopan et al. (2021)
Karanj seed	34.56	90.27	Gopan et al. (2020)
Castor seed	58.61	92.54	Jayant et al. (2021)

3.6 Enhanced Utilization of Ingredients

The feed intake and digestibility are affected by the anti-nutrients and fiber present in the ingredients and diet. The inclusion of plant-based ingredients in the diet can adversely affect digestion and nutrient utilization. Increased utilization of nutrients and feed conversion efficiency are the best strategies to cope with the changing climatic conditions. For enhanced utilization of plant-based ingredients, solid-state fermentation of ingredients, application of exogenous enzymes, soaking, and extraction of proteins from ingredients can be adapted. Meshram et al. (2018) reported that solid-state fermentation of leafmeal with *Chaetomium globosum* enhanced the growth and feed efficiency in rohu fingerlings. Similarly, feeding of 0.1% exogenous enzymes (xylanase and cellulase) in leafmeal-based fish feed improved the nutrient utilization in *L. rohita* fingerlings (Maiti et al. 2019). Alternate feeding strategies and feeding of metabolic modifiers can also enhance feed utilization efficiency in fish.

4 Precision Nutrition

The term "precision nutrition" refers to the precise delivery of nutrients to animals to meet their requirements and confer maximum growth and health. This can be achieved through the use of precise feed formulations, advanced feed processing techniques, and targeted nutrient delivery systems (Reddy and Krishna 2009). The concept describes the most suitable feed for the species based on its life stage and environment. Changes in temperature or exposure to stressors can result in changes in the nutritional requirements of fish. Hence, understanding the nutritional requirements of fish according to their environment and the precise estimation of nutritional requirements with the application of high-throughput technologies like nutrigenomics will help in formulating precise feed for fish. Moreover, by depicting the molecular basis and regulatory pathways of various nutrients, the nutritional quality of farmed fish can be improved (Zheng et al. 2009). For example, changes in water temperature can alter the structural fatty acids of fish. Hence, the feed formulation should address the requirements of species accordingly. The addition of an optimal dose of nutraceuticals like exogenous enzymes, vitamins, minerals, etc. in the diet can enhance digestibility and mitigate the effect of thermal stress exposure in fish competently. Changes in environmental temperature and fluctuations in climate patterns may alter the metabolic rate and physiology of fish. The development of automatic feeding devices based on artificial intelligence (AI) and the Internet of Things (IoTs), which sense the temperature change and subsequent metabolic rate or physiological variation in fish, can deliver the required nutrients to the animals without fail (Zhang et al. 2020). Machine learning and the application of artificial intelligence in aquafeed formulations can contribute to precision feeding. Similarly, sensors that can detect changes in the physiology of the fish due to nutritional deficiency, disease, or starvation can also be helpful in managing feed. Therefore, the adaptation of precision nutrition is the need of the hour in aquaculture to meet future needs due to climate change.

5 Genetic Selection of Species

Genetic variability is a major factor that differentiates the plastic responses, like reproductive timings, rate of growth, etc., among families, populations, or within species (Jensen et al. 2008; Hutchings 2011). The prolonged exposure to stressors due to climate change may result in phenotypic changes and the plasticity in stress tolerance becomes acclimation, which can further lead to local adaptation or tolerance (Kassahan et al., 2012). Although there is a difference in such responses among various species, it is evident that genetic changes in response to temperature fluctuations can be adaptive (Crozier and Hutchings 2014). For example, thermal tolerance in killifish in response to repeated exposure to a warm temperature (Healy and Schulte 2012) and almost constant temperature in antarctic fishes (Bilyk and DeVries 2011) indicate that genomic plasticity exists in fish. Hence, selection of species based on temperature associated SNPs (single nucleotide polymorphisms), immune genes, or feed efficiency can result in faster adaptation, as observed in three-spined stickleback which exhibited a cold tolerance within 3 generations (Barrett et al. 2011). Traits like heat tolerance, feed conversion efficiency, and thermal response for growth can yield measurable selection responses and can be employed in the genetic selection process of fish on the basis of climate change (Ineno et al. 2008; Kavanagh et al. 2010).

6 Conclusion

The vulnerability of aquaculture systems to climate change can be reduced by improving the resilience of aquaculture systems, modifying the feed formulation with potential ingredients and functional additives, and reducing waste generation.

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References

Akhtar MS, Kumar Pal A, Sahu NP, Ciji A, Kumar N (2012) Effects of dietary pyridoxine on haemato-immunological responses of *Labeo rohita* fingerlings reared at higher water temperature. J Anim Physiol Anim Nutr 96(4):581–590

Akhtar MS, Pal AK, Sahu NP, Ciji A, Mahanta PC (2013a) Thermal tolerance, oxygen consumption and haemato-biochemical variables of tor putitora juveniles acclimated to five temperatures. Fish Physiol Biochem 39(6):1387–1398

Akhtar MS, Pal AK, Sahu NP, Ciji A, Meena DK, Das P (2013b) Physiological responses of dietary tryptophan fed Labeo rohita to temperature and salinity stress. J Anim Physiol Anim Nutr 97(6): 1075–1083

Barrett RDH, Paccard A, Healy TM, Bergek S, Schulte PM, Schluter D, Rogers SM (2011) Rapid evolution of cold tolerance in stickleback. Proc Biol Sci 278:233–238

Bilyk KT, DeVries AL (2011) Heat tolerance and its plasticity in Antarctic fishes. Comp Biochem Physiol A Mol Integr Physiol 158:382–390

Bruni L, Pastorelli R, Viti C, Gasco L, Parisi G (2018) Characterisation of the intestinal microbial communities of rainbow trout (Oncorhynchus mykiss) fed with *Hermetia illucens* (black soldier fly) partially defatted larva meal as partial dietary protein source. Aquaculture 487:56–63. https://doi.org/10.1016/j.aquaculture.2018.01.006

Butt RL, Volkoff H (2019) Gut microbiota and energy homeostasis in fish. Front Endocrinol (Lausanne) 10:9

Cheng CH, Guo ZX, Ye CX, Wang AL (2018) Effect of dietary astaxanthin on the growth performance, non-specific immunity, and antioxidant capacity of pufferfish (*Takifugu obscurus*) under high temperature stress. Fish Physiol Biochem 44(1):209–218

Ciji A, Akhtar MS (2021) Stress management in aquaculture: a review of dietary interventions. Rev Aquac 13(4):2190–2247

Corrêa CF, Nobrega RO, Mattioni B, Block JM, Fracalossi DM (2017) Dietary lipid sources affect the performance of Nile tilapia at optimal and cold, suboptimal temperatures. Aquacult Nutr 23(5):1016–1026

Corrêa CF, Nobrega RO, Block JM, Fracalossi DM (2018) Mixes of plant oils as fish oil substitutes for Nile tilapia at optimal and cold suboptimal temperature. Aquaculture 497:82–90

Crozier LG, Hutchings JA (2014) Plastic and evolutionary responses to climate change in fish. Evol Appl 7(1):68–87. https://doi.org/10.1111/eva.12135

Das T, Pal AK, Chakraborty SK, Manush SM, Sahu NP, Mukherjee SC (2005) Thermal tolerance, growth and oxygen consumption of *Labeo rohita* fry (Hamilton, 1822) acclimated to four temperatures. J Therm Biol 30(5):378–383

Dawood MAO, Koshio S, Esteban MA (2018) Beneficial roles of feed additives as immunostimulants in aquaculture: a review. Rev Aquac 10:950–974

Debnath D, Pal AK, Sahu NP, Baruah K, Yengkokpam S, Das T, Manush SM (2006) Thermal tolerance and metabolic activity of yellowtail catfish *Pangasius pangasius* (Hamilton) advanced fingerlings with emphasis on their culture potential. Aquaculture 258(1–4):606–610

Fawole FJ, Sahu NP, Pal AK, Ravindran A (2016) Haemato-immunological response of Labeo rohita (Hamilton) fingerlings fed leaf extracts and challenged by Aeromonas hydrophila. Aquac Res 47(12):3788–3799

Fawole FJ, Sahu NP, Shamna N, Phulia V, Emikpe BO, Adeoye AA, Popoola OM et al (2018) Effects of detoxified Jatropha curcas protein isolate on growth performance, nutrient digestibility and physio-metabolic response of *Labeo rohita* fingerlings. Aquacult Nutr 24(4):1223–1233

Gerasimidis K, Fillou DT, Babatzimcpoulou M, Tassou K, Katsikas H (2007) Preparation of an edible cottonseed protein concentrate and evaluation of its functional properties. Int J Food Sci Nutr 58(6):486–490

Gopan A, Sahu NP, Varghese T, Sardar P, Maiti MK (2020) Karanj protein isolate prepared from karanj seed cake: effect on growth, body composition and physiometabolic responses in *Labeo rohita* fingerlings. Aquacult Nutr 26(3):737–751

Gopan A, Maiti MK, Varghese T, Lalappan S, Sardar P, Gupta S, Sahu NP (2021) Nutritional evaluation of protein isolate from neem seed cake in Labeo rohita (Hamilton, 1822) fingerlings concomitant with oil extraction processing industry. Anim Feed Sci Technol 274:114858

Hao T, Wang L, Wang J, Li B, Ma J, Wang S, Zhang L et al (2017) Effects of dietary vitamin C supplementation on hypothalamic-pituitary-interrenal axis and physiological indices of juvenile hybrid grouper Epinephelus lanceolatu♂× Epinephelus fuscoguttatus♀ under acute low temperature stress. J Fish China 41(3):428–437

Hassan MS, Nagar AGE, Salim HS, Fitzsimmons K, El-Haroun ER (2019) Nutritional mitigation of winter thermal stress in Nile tilapia by propolis-extract: associated indicators of nutritional status, physiological responses and transcriptional response of delta-9-desaturase gene. Aquaculture 511:734256

Healy TM, Schulte PM (2012) Factors affecting plasticity in whole-organism thermal tolerance in common killifish (*Fundulus heteroclitus*). J Comp Physiol B 182(1):49–62

Hoseinifar SH, Doan HV, DadarM RE, Harikrishnan R (2019) Feed additives, gut microbiota and health in finfish aquaculture. In: Microbial communities in aquaculture ecosystems. Springer, Cham, pp 121–142

Hutchings JA (2011) Old wine in new bottles: reaction norms in salmonid fishes. Heredity (Edinb) 106(3):421–437

Huyben D, Vidaković A, Hallgren SW, Langeland M (2019) High-throughput sequencing of gut microbiota in rainbow trout (*Oncorhynchus mykiss*) fed larval and pre-pupae stages of black soldier fly (*Hermetia illucens*). Aquaculture 500:485–491

Ineno T, Endo M, Watabe S (2008) Differences in self-feeding activity between thermally selected and normal strains of rainbow trout *Oncorhynchus mykiss* at high temperatures. Fish Sci 74: 372–379

Islam MJ, Kunzmann A, Slater MJ (2021) Responses of aquaculture fish to climate change-induced extreme temperatures: a review. J World Aquacult Soc 53:314

Jayant M, Sahu NP, Deo AD, Gupta S, Rajendran KV, Garg CK, Wagde MS (2021) Effective valorization of bio-processed castor kernel meal based fish feed supplements concomitant with oil extraction processing industry: a prolific way towards greening of landscaping/environment. Environ Technol Innov 21:101320

Jensen LF, Hansen MM, Pertoldi C, Holdensgaard G, Mensberg KL, Loeschcke V (2008) Local adaptation in brown trout early life-history traits: implications for climate change adaptability. Proc Biol Sci 275(1653):2859–2868

Jobling M (1995) Simple indices for the assessment of the influences of social environment on growth performance, exemplified by studies on Arctic charr. Aquac Int 3(1):60–65

Kassahun DA, Waidbacher H, Munguti JM, Zollitsch WJ (2012) Locally available feedstuff's for smallscale aquaculture in Ethiopia-a review. Die Bodenkultur 51(63):2–3

Kassahn KS, Crozier RH, Pörtner HO, Caley MJ (2009) Animal performance and stress: responses and tolerance limits at different levels of biological organisation. Biol Rev Camb Philos Soc 84(2):277–292

Kausar R, Salim M (2006) Effect of water temperature on the growth performance and feed conversion ratio of *Labeo rohita*. Pakistan Vet J 26(3):105–108

Kavanagh KD, Haugen TO, Gregersen F, Jernvall J, Vollestad LA (2010) Contemporary temperature-driven divergence in a Nordic freshwater fish under conditions commonly thought to hinder adaptation. BMC Evol Biol 10:350

Kelly C, Salinas I (2017) Under pressure: interactions between commensal microbiota and the teleost immune system. Front Immunol 8:559

Kidd PM (2000) The use of mushroom glucans and proteoglycans in cancer treatment. Altern Med Rev 5(1):4–27

Kumar P, Saurabh S, Pal AK, Sahu NP, Arasu ART (2014) Stress mitigating and growth enhancing effect of dietary tryptophan in rohu (*Labeo rohita*, Hamilton, 1822) fingerlings. Fish Physiol Biochem 40(5):1325–1338

Lee YK, Mazmanian SK (2014) Microbial learning lessons: SFB educate the immune system. Immunity 40(4):457–459

Madeira D, Vinagre C, Diniz MS (2016) Are fish in hot water? Effects of warming on oxidative stress metabolism in the commercial species *Sparus aurata*. Ecol Indic 63:324–331

Maiti MK, Sahu NP, Sardar P, Shamna N, Deo AD, Gopan A, Sahoo S (2019) Optimum utilization of *Hygrophila spinosa* leaf meal in the diet of *Labeo rohita* (Hamilton, 1822) fingerlings. Aquac Rep 15:100213

Manush SM, Pal AK, Chatterjee N, Das T, Mukherjee SC (2004) Thermal tolerance and oxygen consumption of Macrobrachium rosenbergii acclimated to three temperatures. J Therm Biol 29 (1):15–19

Meshram S, Deo AD, Kumar S, Aklakur M, Sahu NP (2018) Replacement of de-oiled rice bran by soaked and fermented sweet potato leaf meal: effect on growth performance, body composition and expression of insulin-like growth factor 1 in *Labeo rohita* (Hamilton), fingerlings. Aquacult Res 49(8):2741–2750

Miao S, Zhao C, Zhu J, Hu J, Dong X, Sun L (2018) Dietary soybean meal affects intestinal homoeostasis by altering the microbiota, morphology and inflammatory cytokine gene expression in northern snakehead. Sci Rep 8:1–10. https://doi.org/10.1038/s41598-017-18430-7

Nowicki R, Heithaus M, Thomson J, Burkholder D, Gastrich K, Wirsing A (2019) Indirect legacy effects of an extreme climatic event on a marine megafaunal community. Ecol Monogr 89(3): e01365. https://doi.org/10.1002/ecm.1365

Ortuño J, Esteban MA, Meseguer J (2003) The effect of dietary intake of vitamins C and E on the stress response of gilthead seabream (*Sparus aurata* L.). Fish Shellfish Immunol 14(2):145–156

Perry WB, Lindsay E, Payne CJ, Brodie C, Kazlauskaite R (2020) The role of the gut microbiome in sustainable teleost aquaculture. Proc R Soc B 287:20200184. https://doi.org/10.1098/rspb.2020.0184

Pörtner HO, Peck MA (2010) Climate change effects on fishes and fisheries: towards a cause-and-effect understanding. J Fish Biol 77(8):1745–1779

Ray AK, Ghosh K, Ringø E (2012) Enzyme-producing bacteria isolated from fish gut: a review. Aquacult Nutr 18:465–492. https://doi.org/10.1111/j.1365-2095.2012.00943.x

Reddy DV, Krishna N (2009) Precision animal nutrition: a tool for economic and eco-friendly animal production in ruminants. Livest Res Rural Dev 21:203–222

Sarma K, Pal AK, Sahu NP, Ayyappan S, Baruah K (2009) Dietary high protein and vitamin C mitigates endosulfan toxicity in the spotted murrel, *Channa punctatus* (Bloch, 1793). Sci Total Environ 407(12):3668–3673

Schrama D, Richard N, Silva TS, Figueiredo FA, Conceição LE, Burchmore R, Rodrigues PM et al (2017) Enhanced dietary formulation to mitigate winter thermal stress in gilthead sea bream (*Sparus aurata*): a 2D-DIGE plasma proteome study. Fish Physiol Biochem 43(2):603–617

Šegvić-Bubić T, Boban J, Grubišić L, Trumbić Ž, Radman M, Perčić M, Čož-Rakovac R (2013) Effects of propolis enriched diet on growth performance and plasma biochemical parameters of juvenile European sea bass (*Dicentrarchus labrax* L.) under acute low-temperature stress. Aquacult Nutr 19(6):877–885

Shamna N, Sardar P, Sahu NP, Pal AK, Jain KK, Phulia V (2015) Nutritional evaluation of fermented Jatropha protein concentrate in *Labeo rohita* fingerlings. Aquacult Nutr 21(1):33–42

Shamna N, Sardar P, Sahu NP, Phulia V, Rajesh M, Fawole FJ, Angel G et al (2017) Heamato-immunological and physiological responses of *Labeo rohita* fingerlings to dietary fermented Jatropha curcas protein concentrate. Anim Feed Sci Technol 232:198–206

Shamna N, Prasad Sahu N, Sardar P, Fawole FJ, Kumar S (2020) Additional feeding of vitamin–mineral-based nutraceutical to stress-exposed rohu, *Labeo rohita*, enhances the IGF-1 gene expression and growth. Aquacult Res 51(7):2649–2666

Shamna N, Sahu NP, Sardar P, Fawole FJ (2021) Effects of nutraceutical conglomerate on growth and antioxidant status of *Labeo rohita* fingerlings. Anim Feed Sci Technol 280:115045

Shen G, Huang Y, Dong J, Wang X, Cheng KK, Feng J, Ye J et al (2018) Metabolic effect of dietary taurine supplementation on Nile tilapia (*Oreochromis nilotictus*) evaluated by NMR-based metabolomics. J Agric Food Chem 66(1):368–377

Shrivastava J, Sinha AK, Cannaerts S, Blust R, De Boeck G (2017) Temporal assessment of metabolic rate, ammonia dynamics and ion-status in common carp during fasting: a promising approach for optimizing fasting episode prior to fish transportation. Aquaculture 48:218–228

Tort L, Rotllant J, Liarte C, Acerete L, Hernández A, Ceulemans S, Padrós F et al (2004) Effects of temperature decrease on feeding rates, immune indicators and histopathological changes of gilthead sea bream *Sparus aurata* fed with an experimental diet. Aquaculture 229(1–4):55–65

Verma AK, Pal AK, Manush SM, Das T, Dalvi RS, Chandrachoodan PP, Apte SK et al (2007) Persistent sub-lethal chlorine exposure augments temperature induced immunosuppression in Cyprinus carpio advanced fingerlings. Fish Shellfish Immunol 22(5):547–555

Vijayan MM, Pereira C, Forsyth RB, Kennedy CJ, Iwama GK (1997) Handling stress does not affect the expression of hepatic heat shock protein 70 and conjugation enzymes in rainbow trout treated with β-naphthoflavone. Life Sci 61(2):117–127

Wang AR, Ran C, Ringø E, Zhou ZG (2018) Progress in fish gastrointestinal microbiota research. Rev Aquac 10(3):626–640

Wendelaar Bonga SE (1997) The stress response in fish. Physiol Rev 77(3):591–625

Wu S, Ren Y, Peng C, Hao Y, Xiong F, Wang G, Li W, Zou H, Angert ER (2015) Metatranscriptomic discovery of plant biomass-degrading capacity from grass carp intestinal microbiomes. FEMS Microbiol Ecol 91(5):107. https://doi.org/10.1093/femsec/fiv107

Xia JH, Lin G, Fu GH, Wan ZY, Lee M, Wang L, Yue GH et al (2014) The intestinal microbiome of fish under starvation. BMC Genomics 15(1):1–11

Ye JD, Wang K, Li FD, Sun YZ (2011) Single or combined effects of fructo- and mannan oligosaccharide supplements and *Bacillus clausii* on the growth, feed utilization, body composition, digestive enzyme activity, innate immune response and lipid metabolism of Japanese flounder Paralichthys olivaceus. Aquacult Nutr 17:902–911

Yukgehnaish K, Kumar P, Sivachandran P, Marimuth K, Arshad A, Paray BA, Arockiaraj J (2020) Gut microbiota metagenomics in aquaculture: factors influencing gut microbiome and its physiological role in fish. Rev Aquac 12(3):1903–1927

Zhang Y, Lu R, Qin C, Nie G (2020) Precision nutritional regulation and aquaculture. Aquac Rep 18:100496

Zheng X, Leaver MJ, Tocher DR (2009) Long-chain polyunsaturated fatty acid synthesis in fish: comparative analysis of Atlantic salmon (*Salmo salar* L.) and Atlantic cod (Gadus morhua L.) Δ6 fatty acyl desaturase gene promoters. Comp Biochem Physiol B Biochem Mol Biol 154: 255–263

Live Duckweed-Based Circular Aquaculture for Climate Resilience and Carbon Footprint Reduction of Fed Aquaculture

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Abstract

Aquaculture in recent decades has shown impressive growth and currently supplies half of the global food fish supply. The growth of aquaculture is driven by fed aquaculture whose contribution has increased from 56% in 2000 to 70% in 2018. Fed aquaculture is likely to drive the aquaculture growth as push towards productivity enhancement will further intensify for food and nutrition security reasons in the wake of diminishing per capita land and water resources vis-à-vis the burgeoning global population. Feed, besides representing the single largest operating cost, also represents the largest source of greenhouse gas and consequent carbon footprint of aquaculture. With greater adoption of more complex and commercial feeds including extruded feeds which are more energy-intensive and require greater energy to produce per unit feed, the carbon footprint of feed also is likely to increase. The present article analyzes the carbon footprint of fed aquaculture, especially in tropical countries. In this regard, it is further notable that only a narrow range of conventional feed ingredients are utilized for aquaculture feed and are commonly outsourced from long distances often involving roadways in hilly and mountainous terrains. Such long distance transports are substantial contributors to the carbon footprint. We propose that on-farm and/or local production of Wolffia globosa and its utilization in live form can substantially reduce the carbon footprint of aquaculture by eliminating all the energy requirements for processing and storage vis-a-vis long distance transports. Further, growing duckweed can be a carbon sequester and could aid the sustainable development of aquaculture.

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Aquaculture · Carbon footprint · Carbon sequestration · Bio-circular economy

1 Introduction

Aquaculture, is the fastest-growing major world food sector and contributes significantly to not only food and nutritional security by increasing the fish availability per capita but also livelihood security by promoting economic development and employment, particularly in rural areas. While the production from fisheries has almost stagnated, the production of farmed aquatic animals in aquaculture grew on average at 5.3% per year between 2001 and 2018 (FAO 2020). Aquaculture is likely to play an even more dominant role in meeting the increased fish demand of the burgeoning human population which is further facilitated by increased urbanization, better transportation networks, and higher income and standard of living. The major increase in aquaculture has been achieved by increased production from fed aquaculture which is the main driver of aquaculture growth whose contribution has increased from 56.1% in 2000 to 69.5% in 2018 (FAO 2020). Intensification including the adoption of fed aquaculture is the future of aquaculture in light of reduced land and water availability. However, it is widely believed that intensive fed aquaculture is inherently imbalanced and unsustainable. To ensure sustainable growth of fed aquaculture, it is important to develop not only more efficient input systems, production management systems, and location-specific technologies but also environmental and social impact assessments. Further, to enable sustainable expansion of aquaculture, we need to understand aquaculture's contribution to global GHG emissions and how they can be mitigated.

All the modern food production enterprises including intensive aquaculture which are increasingly input and management intensive have ecological impacts. The ecological impact of any enterprise is measured by the carbon footprint (CFP) which takes the consumption of natural resources and energy by the concerned activities and enterprises into account (Wackernagel and Rees 1998). The CFP of an enterprise or activity is measured as the total greenhouse gases released over the production of concerned product during its entire life cycle based on the cradle to the grave concept. This involves resource or energy use starting from the initiations of the production process including preparation of the ecosystem, collection and transportation of raw materials, processing, manufacturing, and transportation of finished products, viz. feed, and the harvest of produce and waste disposal (Williams 2009). Carbon footprints are utilized for inter-sectoral comparisons to rank the enterprises based on their environmental friendliness. It is striking to note that great diversity in the level of intensification of aquaculture in terms of use of resource, energy, and management interventions exists, and hence, it is difficult to work out a universal CFP for aquaculture enterprise. It has to be based on a micro-analysis of the resource and energy use and their acquisitions for the purpose which may lead to higher or lower contribution of specific interventions or aspects of the production. However, among feed-lot livestock production systems including poultry, pig, beef, etc., and fed aquaculture systems, feed is considered to be the dominant contributor to the carbon footprint in its life cycle emissions (Galli et al. 2012).

2 Carbon Footprint from Modern Aquaculture

The carbon dioxide concentrations, approximately 280 parts per million (ppm) in the mid-1970s, increased to 316 ppm in 1960 and then to 394 ppm in 2010 (Boyd 2013). The increase of the increasing population is primarily attributed to the impetus to establishment and intensification of modern more energy-intensive, often based on fossil fuels, industries, and enterprises including agriculture and increased goods movement activities at high throughput and productivities in the post-industrial revolution. For that matter, the terrestrial livestock supply chains were responsible for the production of 7.1 Gt CO_2e (carbon dioxide equivalent) per annum (Gerber et al. 2013), with major emissions arising from enteric fermentation, production of feed as well as manure management. Conversely, no concrete quantitative value of CO_2e is available for aquaculture despite the fact that it is the quickest growing food sector. However, in recent years studies have been undertaken to assess the CHG emission and CFP of some aquaculture commodities, particularly marine species such as salmon and shrimp. Not much comprehensive information is available for freshwater fish species such as the Nile tilapia, Indian major carps, and striped catfish. GHG emissions from aquaculture arise during pre-stocking, stocking, and post-stocking periods including production of all raw materials such as energy consumed in the cultivation of feed ingredient production, in capturing fish to produce fishmeal as well as during subsequent processing and transportation. Further, unlike in that terrestrial live stocks, the feed production in aquaculture consumes a high amount of energy to grind and mix the raw materials, prepare the pellets, and dry them. The total energy which is being used depends on local production or outsourcing vis-à-vis production efficiencies. Energy is further consumed in transportation and sometimes re-transportation back to the place from ingredients sourced from commercial feeds as well as to convey the feed to the farms.

Aquaculture farms are located in different sites primarily based on the suitability of species and availability of land and water and at times also driven by economic considerations. An effort is to ensure a good environment and water quality matching the requirements of the species to protect the farmed animals from diseases. Poor water quality may lead to not only efficiency but also to an increase in GHG emissions owing to excess nutrient loss from the system. Similarly, inappropriate feed quality may reduce fish performance and deteriorate the water, thereby increase GHG emissions to great extent. Hence, a well-managed aquaculture pond may greatly reduce the GHG. Notably, aquaculture systems may also act as carbon traps, e.g. if sediments that accumulate and conserve a substantial amount of organic matter including dead plankton are later used in agriculture. Similarly, there is great variability in the use of feed resources, thus making GHG emission accounting, even more, complex (Verdegem and Bosma 2009). After harvesting of fish, they may be sold in local markets or transported to market in one of the three conditions, viz. live, iced, or processed. These also entail different levels of GHG emissions. As could be expected, processing not only requires additional energy but may also result in loss of material from the system, which may in turn, increase the CFP [EI (kg of CO_2e per kg of product)] of the final product. Conversely, transportation which is involved at multiple stages also entails substantial energy consumption leading to elevated CFP of aquaculture. For that matter, it is estimated that about 0.09 kg CO_2 eq t km^{-1} fossil fuels are burnt for transportation (Liu et al. 2016). In this regard, it is particularly to highlight that aquaculture feed is heavily reliant on select conventional feed ingredients which have to be often sourced from long distances not only when international trades are involved as is the case of soybean meal and fishmeal but also in domestic movements of bulk ingredients such as grains and their byproducts especially in countries with large geographical areas such as India, China, and etc. Accordingly, aquaculture-reliant feed resources which are produced locally or outsourced and require low or high levels of processing would have a great influence on the CFP of fed aquaculture.

In general, emissions from aquaculture at the global level are remarkably low as compared to that of livestock primarily because of great differences in the scale of production, viz. the volume of aquaculture production is markedly low in comparison to combined livestock production. For that matter, in the year 2013, aquatic animals accounted only for 7% of global protein intake, approx. Half of which was from aquaculture, compared to 33% of protein from livestock products (FAO 2017). Further, aquaculture has relatively low emission intensity in comparison to livestock. The livestock has particularly high maintenance energy requirements and consequently a high feed conversion ratio indicating lower biomass conversion efficiency from feeds. Further, beef and cattle being ruminant animals produce methane via enteric fermentation. The CFP is further enhanced by inefficient transformation of the plant energy, feed production, and manure management. The carbon footprints of capture fisheries and aquaculture have been reported to be in the range of 1–3 against 2–7 kg carbon dioxide per kg of meat. However, certain intensive fed aquaculture production like shrimp production has been identified with markedly higher emissions, viz. 3.0799 $kgCO_2$/100 kcal compared to followed by 2.5900 $kgCO_2$/100 kcal for lamb, 1.3789 $kgCO_2$/100 kcal for beef, and 0.9026 $kgCO_2$/100 kcal for pork. But it is notable that fish flesh is less energy-dense, and carbon dioxide emission when compared on the basis of kg carbon dioxide/kg meat, aquaculture produced shrimp, tipalia, channel catfish salmon has been reported to have values ranging 2–7, and wild caught fish as 1–3, in comparison to beef, pork, and chicken having values of 12–16, 4–8, and 3–4, respectively. Accordingly, there is a particular need to address the high carbon emissions associated with shrimp production by improving the efficiency of resource and energy use and developing a more sustainable approach to production and its distribution. Notably, a large portion of the emission of GHG in shrimp farming is attributed to high electricity consumption in the aquaculture phase and subsequent production of energy-intensive feeds. In comparison to shrimp, salmon farming has relatively lower carbon emissions as its farming is often practiced in ocean cages where there is limited use of electricity due to natural flushing off of waters which brings dissolved oxygen as well as the need for water exchange. Those waste effluents generated are being driven away by the ocean currents that minimize the dependence on waste treatment plants with more emphasis on the use of wind and tidal energy resources. Thus, to promote sustainable aquaculture, we must be aware of aquaculture's contribution to global GHG emissions, and further, approaches to be made on how they can be mitigated (Gerber et al. 2013). For instance, alternative renewal energy sources with lower CFP, and the use of locally available feed materials/ingredients, especially in live form or with minimal processing may reduce aquaculture's carbon footprint after taking the life cycle assessment (LCA) into account.

3 Emissions from the Production of Feed Materials

In general, feed and mechanical aeration represent the most dominant contributor to the CFP of intensified aquaculture (Hagos 2012). Remarkably, the production of crop feed materials accounted for 39% and cumulative contributions including the emissions from fishmeal production, feed blending, and transport up to 57% of total aquaculture emissions in 2017 (MacLeod et al. 2020). As a concern, the non-feed emissions mostly are accounted for by nitrification and denitrification of nitrogenous compounds in the aquatic system and the energy used in the fish farm (pumping water, lighting, and powering vehicles) (FAO 2017). Feed and feeding have also been identified as the single most dominant source of emissions for carps in India. It has been documented to account for 43% of the EI for Indian carps. It is notable that the CFP on accounts of the feed materials is primarily a function of two factors: (1) the EI of the production feed materials including processing and production of powder or pellet, viz. kg CO_2e per kg of feed) and (2) the feed conversion ratio, viz. the quantity of feed (kg) required to produce 1 kg of live weight (LW) fish. Carp rations are often associated with high proportions of high EI grains maize and broken rice with a cumulative contribution up to 40–50% and smaller but significant amounts of cakes of ground nut with higher EI than other oilseed meals.

4 Emissions from the Transport of Feed Materials

Long distance transports of feed ingredients, often involving different countries, are realities of modern fed aquaculture Emissions arising from the transport of feed material from place of production to the feed mill vary from place to place. In general, outsourced feed ingredients quite dominate the feed industry, especially with respect to protein sources. For that matter, Bangladesh imports a great quantity of soy from the USA and meat and bone meal from the European Union, while countries like China and Vietnam import large quantities of soy from the USA and Argentina. In comparison to these countries, India does not import as many feed ingredients from other countries and consequently transport emissions are seen as relatively lower for the Indian carps rations due to the predominance of domestically produced feeds in this system. However, it is important to note that there are remarkable internal movements and transportation of conventional feed ingredients within the country. This happens primarily because great variabilities in agroclimatic conditions and the development state of irrigation facilities mean that many conventional ingredients could not be produced at all or in sufficient quantity necessitating long-distance transportation. For instance, the entire northeastern region is dominated by hilly terrain, lower temperature regime coupled with poorly developed irrigation facilities means the region is greatly deficient in the production of these conventional feed ingredients. This has meant that fed aquaculture in the entire north region is primarily dependent on outsourced conventional feed ingredients and/or commercial feeds covering large distance transports involving road transports covering a distance of 2000-3000 km.

5 Emissions from Energy Use in the Feed Mill

The production of modern fish feed entails substantial processing of feed ingredients subsequent to their arrival at the feed mill including drying, grinding, mixing, conditioning, pelleting, drying, cooling, and packaging. The energy requirements and variations there in the feed mill greatly vary depending on the type of feed materials and quality of feeds, grinding, manufacturing method whether compression or extrusion and pellet size. Notably, extrusion requires 30–40% more energy per biomass of feed produced in comparison to that of compression. The rates of energy consumption in the feed mill also depend on the quality of the fuels used. India and Vietnam made use of energy in the form of biomass which gives relatively low-quality fuels characterized by low energy density and low conversion efficiencies. However, biomass is theoretically assumed to have zero net GHG emissions, therefore helping to lower the overall EI of the feed. But in the case of India, such an emission reduction is offset by a relatively higher electricity emission factor.

6 Emissions from Transport of Feed from Mill to Farm

The distance of travel of feeds as well as mode of transport determines the contribution of this step to the overall emissions. Till recently, the adoption of commercial feed-based aquaculture has been relatively low in India due to multiple reasons including the dominance of small and marginal scale farmers who are unable to afford commercial feeds. Conversely, shrimp production is primarily based on commercial feeds. Taking these into accounts, feed mills in India had primarily been located in the southern and coastal regions of the country. Accordingly, India has mostly been identified with the short average transport distance of feed from mill to farm (44 km). However, this is changing at a fast rate as pelleted feeds are gaining popularity and wide adoption. The feed mills realizing the opportunity are aggressively developing and marketing the feeds for freshwater fishes like carps and catfishes. However, the demand for feed for freshwater fishes in many regions is still below the critical level for the establishment of large-scale feed industry. The lack of pre-requisite infrastructural facilities includes stable electricity and other allied facilities. As a result, there has been a spurt in long-distance transport of feeds. The longest distance of transport of fish feeds could be as high as 2000 km and beyond. For that matter, in recent years large distance transport of feeds produced in southern states of Andhra Pradesh and Tamil Nadu is being transported to northeastern region traveling by road which is notoriously less fuel-efficient, and hence, has high emission per tonnage of transport, compared to shipping using waterways. Thus, unless long-distance sourcing is addressed, such long-distance transport of feeds is likely to greatly enhance the GHG emission of fed aquaculture.

7 On-Farm Production of Duckweed and its Utilization as Feed

Indian aquaculture production is dominated by the three Indian major carps, namely *Labeo rohita, Catla catla*, and *Cirrhinus mrigala* which togethor contribute about 87% of the total freshwater production in the country. The Chinese carps including *Cyprinus carpio, Hypophthalmichthys molitrix, Ctenopharyngodon Idella* are the next dominant contributors. Further, in recent times several other medium and minor carps including *Osteobrama belangeri, Labeo gonius, Barbonymus gonionotus,* etc. have emerged as potential aquaculture species. Carps feed low in the food chain including plankton, periphyton, detritus, macroalgae, and aquatic plants and are mostly raised in earthen ponds under polyculture. While autochthonously produced natural foods of the pond serve as an important source of nutrition to carps, supplementary feeds are employed for augmentation of productivity.

Duckweeds (family Lemnaceae), a widely distributed floating aquatic plant, are characterized by small size, high turnover rates, favorable nutritional profile including relatively high protein (20–40%) with preferable essential amino acid profile, low fiber content, rich content of bioactive compounds. Duckweeds are a free-floating aquatic plant that proliferates through vegetative budding of new fronds and produces biomass faster than most other plants in wide-ranging tropical to subtropical agroclimatic conditions (Landolt 1986). It can grow year-round at faster growth rates than most field crops and can double its biomass within 2 days under optimal conditions (Landolt 1986; Landesman et al. 2005). In particular, wolffia, a member of duckweed and the smallest flowering plant on the earth, is widely consumed directly in the live form of a complete nutritional package that has shown to result in comparable combined yield in a polyculture system. Further, it can be grown throughout the year in tropical–subtropical agroclimatic conditions at high turnover rates and serve as a renewal feed resource (Journey et al. 1991) that

Fig. 1 Duckweed culture pond at COF, Tripura

Fig. 2 Harvested live wolffia

can be harvested easily (Xue et al. 2014). We at the college of Fisheries, Central Agricultural University, Lembucherra, have evaluated and observed that live *Wolffia globosa* could completely replace supplementary feed inputs during seed rearing as well as grow-out of several carps including rohu, pengba (*Osteobrama belangeri*), Amur common carp (*Cyprinus carpio*), silver barb (*Barbonymous gonionotus*), etc. Thus, their local production in the vicinity of the aquaculture farm would remarkably reduce the need for transportation while will also serve as a carbon sink due to their ability to take up carbon dioxide from both atmospheres and water. Further, their use in live form also eliminates the energy requirements in processing and feed production (Figs. 1 and 2). In this regard, we have established pilot scale culture of wolffia production at the College farm (Fig. 1). The live wolffia is easily harvested on daily basis at a production rate of about 100-150 g m^{-2} d^{-1} basis and accumulated in any suitable container (Fig. 2) and are utilizing in live form to feed.

8 Carbon Sequestration

Carbon sequestration represents absorption and storing of atmospheric carbon dioxide, and hence, is associated mitigation of global warming and climate change (USGS—the United States Geological Survey). Biologic sequestration assists in removing CO_2 from the atmosphere by boosting the growth of plants, Duckweeds are capable of fixing carbon from the atmosphere by different processes such as producing biofuels, biogas, and absorbing dissolved nutrients from wastewater (Kanoun-Boule et al. 2009). Biomass energy represents a green, renewable, and alternative not only to compound feed for fishes but also to fossil fuels because it is a carbon-neutral source of energy (Ren et al. 2018). Biofuels are being utilized for carbon neutrality to create valuable fuels for the transportation sector (Sunny 2017). Developing biofuels from renewable feedstock would also benefit the environment and society (Lynd et al. 1991; Wyman 1994; Nahar 2011) and contribute to lowering CO_2 gas emissions. Assuming the carbon content of duckweed to be 40%, approx. 57.3–155.3 t CO_2 can be removed from the atmosphere by 1 ha of duckweed pond in a year, which makes it one of the potential candidates for CO_2 sequestration. Further, the capture of aquatic carbon dioxide and biomass production systems is the ability to capture CO_2 in ponds in a nongaseous form as bicarbonate which is the dominant form at moderate pH close to 7 and temperatures (below 30 °C) which also stimulates the algal growth. For that matter, algae possess active bicarbonate pumps and can accumulate bicarbonate in the cell. The bicarbonate is subsequently dehydrated. It has been reported that CO_2 in the range of 1.6 and 2 grams is captured for every gram of algal biomass produced (Herzog and Golomb 2004).

9 Circular Bio-Economy

Intensification of agriculture including aquaculture has been associated with eutrophication, pollution, biodiversity losses and overexploitation of natural resources, and climate change (Almond et al. 2020) which has been considered to eventually cause marked disruptions in the food production system itself among a range of other consequences (Kardung et al. 2021). Accordingly, the reduction in ecological footprint caused by human actions has got great attention in recent times (Almond et al. 2020; Cadman et al. 2018). Greater discipline, effort, and research are being called for making the enterprise resource and energy-efficient to reduce ecological footprints.

The development of the bio-economy has been considered to be one of the potential approaches toward amelioration of greenhouse emissions and mitigating climate change. Bio-economy is focused on production systems based on the use of biological resources (biomass) such as food waste or algae for food production (Osmundsen et al. 2020). In the last few years, the European Commission and several industrial associations applied the term “circular bio-economy” and support their integration (Kardung et al. 2021). Circular economy and bio-economy have quite similarities in several points, these two strategies are likely to have common characteristics since they are both based on the use of biological resources as well as show a strong synergy. Generally, bio-based products possess a minor CO_2 footprint than fossil-based analogs and may also help to develop new value chains that can improve the resilience of natural ecosystems (Kardung et al. 2021). Considering that duckweeds can be easily grown on organic manure and/or on other organic wastes and can be an input for aquaculture, it depicts a strong synergy (D'Adamo et al. 2020; Kardung et al. 2021). Notably, food systems occupy the biggest niche of the bio-economy. In the European Union, for instance, food systems such as agriculture, forestry, fisheries, and aquaculture as well as food and feed manufacturing accounted for 71% of all value-added in a bio-economy, followed by approx. 28% for bio-products and the remainder for bio-energy (FAO, Global Forum for Food and Agriculture 2015).

10 Importance of Circular Bio-Economy in Aquaculture

Aquaculture has exhibited impressive growth and acquired a great stature with regard to supply of animal protein in general, and food fish in particular. However, modern feed-based aquaculture production generates huge amounts of waste and the sourcing of feed contributes greatly to the carbon footprint (Dauda et al. 2019). To minimize the environmental impact of the aquaculture system different solutions can be established such as the implementation of the use of green sources for energy supply and the application of circular bio-economy strategies. For that matter, nutrients discharged from an intensive fed system could be utilized for the production of duckweed in general and wolffia in particular which in turn can be utilized as a nutrient resource for certain species. Further, considering the rich contents of a range of bioactive compounds, it can also be a potential renewal resource for applications in cosmetics, pharmacology, and even primary agriculture as manure, or even for creating an integrated multi-trophic aquaculture system. All these approaches would valorize wastes offering additional economic benefits while reducing the environmental impact of aquaculture. The implementation of a circular bio-economy model will provide more sustainable production systems.

11 Duckweed Aquaculture (Wollfia, Lemna, etc.) as a Model for Circular Bio-Economy

Duckweeds are free-floating aquatic plants normally small and fragile. The vegetative reproduction of duckweeds depends on nutrient availability, they rapidly grow when nutrient densities are at a peak and slowly grow where nutrient shortages or key imbalances were observed. Duckweeds are opportunistic in nature while they can grow using flushes of nutrients from intensive aquaculture farms including recirculating aquaculture. Duckweeds consist of four genera: Lemna, Spirodela, Wolfie, and Wolffiella. Around 40 species are well-known worldwide. Several species of it may expand root-like structures in open water places to obtain nutrients in dilute concentrations. In recent years "duckweed," has become well-known aquatic plant, because of its capacity to absorb minerals from heavily polluted water such as from sewage treatment facilities and it has also been paid attention by scientists because of its noticeable potential as a feed source for cultured livestock (Skillicorn et al. 1993; Leng et al. 1994) as well as in aquaculture.

Duckweed aquaculture fits into many crops or animal cultured systems that were managed by small farmers mainly to reduce nutrient loss because it is continuously produced within a short period and can be utilized as fertilizer, food for human consumption, feed for cultured livestock, and also helps to reduce water pollution and water re-use. The duckweeds are not only limited to production and use in cultured ponds but there is also an enormous possibility to produce duckweeds in industrial wastewaters by providing food for the animal production industries and purifying water in that area (Leng 1999).

12 Mitigation of Eutrophication and Wastewater by Duckweeds Culture

Duckweeds have the capability to propagate quickly by absorbing dissolved nutrients from any kind of water, they act as an exceptional "Nutrient Sink" for harvesting nutrients within a short time and serve up as a "Nutrient Pump" especially in wastewater treatment places by absorbing several nutrients like nitrates, phosphates, calcium, potassium, carbon, chloride, etc. from the cultured pond or wastewater. Apart from nutrient extraction from cultured pond or wastewater, it helps to reduce total suspended solids (TSS), biological oxygen demand (BOD), and chemical oxygen demand (COD) significantly. Korner and Vermaat (1998) observed that duckweed culture in any kind of water body place can remove especially nitrates (N) and phosphates (P) at rates of 120–590 mg N/m^2/day and 14–74 mg P/m^2/day within 3 days. Alaerts et al. (1996) also reported the efficiency to remove BOD and ammonia by duckweeds is 96% and 99%.

13 Duckweed as Fish Feed

Duckweed is mainly fed freshly as a feed for cultured fishes and can also be mixed with other feed components to a polyculture system of different Indian and Chinese carp species as well tilapias. The herbivorous and omnivorous fishes like grass carp silver barb and tilapias willingly fed on duckweed. Gijzen and Khondker (1997) reported that the use of duckweed as the feed-in pisciculture was found to be good with a dry weight feed basis mix of 50–60% duckweed and 40–50% supplementary carbohydrate-rich feed. The smaller duckweed species like Wolffia, Wolffiella, and Lemna were reported to serve as feed for fry and fingerlings. Edwards et al. (1990) found that Wolffia and Lemna are mostly used as feed for different sizes of grass carp fingerlings in China. Duckweed as a feed supplement along with commercial

Fig. 3 Live wolffia feeding in carp culture pond at COF, Tripura

feed gave the potential carp yields from carp polycultures in Asia. Galkina et al. (1965) reported a higher yield of pigs, while duckweed was added as a supplement to the daily normal diet. Gijzen and Khondker (1997) observed the use of duckweed as feed for ducks is applied in rural areas. The little amounts (around 2–25% of total dry matter fed) of duckweed fed to chickens enhanced the growth (Haustein et al. 1988). Russoff et al. (1977) found out that duckweed used as a feed additive in daily regular diets for both cattle and sheep could be fed up to 75% of duckweed to cattle without affecting the taste of milk. Duckweeds can be used as compost in the cultured ponds and dried form (Fig. 3).

14 Conclusion

Fed aquaculture contributes to about 70% of fish production of world aquaculture production and is the main driver of aquaculture growth. The contribution of fed aquaculture is likely to consolidate even further in the coming decades for augmentation of aquaculture productivity in the wake of reducing per capita availability of land and water resources. However, the adoption of fed aquaculture in a combination of other interventions including water exchange, aeration, etc. has greatly enhanced the carbon footprint of the modern aquaculture system, feed being one of the most dominant contributors. Unlike much terrestrial livestock, aquaculture feed needs greater processing of ingredients and more energy-intensive pelletization, especially with wide popularity and adoption of extrusion. The carbon footprint is further exacerbated due to long-distance transport that is necessitated due to overreliance on a narrow range of conventional crops whose production itself is water and energy-intensive. Conversely, local production of resources like duckweeds is readily utilized in live form by many carps with relatively high digestive efficiency. The utilization of live duckweeds especially wolffia has a great advantage over conventional feeds by affecting carbon sequestration during its production and eliminating the energy needs during processing and pelletization and allied steps in the production of multi-ingredient aquaculture feed. Further, duckweed like wolffia can be grown on aquaculture effluent, thereby not reducing only the carbon footprint but also ameliorating the eutrophication by stripping nitrogen and phosphorus from the system, in particular at high rates. Thus, there appears to be great scope to reduce the carbon footprint by moving towards the live duckweed-based fish culture involving herbivorous and omnivorous fishes including Indian major carps, Chinese carps, and other emerging species including but not limited to *Osteobrama belangeri*, *Barbonymus gonionotus*. A further refinement, optimization, and promotion of such culture technologies can greatly aid the growth of aquaculture as well by improving the equity of aquaculture to small scale and marginal farmers who are unable to afford commercial feeds.

References

Alaerts GJ, Rehman M, Kelderman P (1996) Performance analysis of a full-scale duckweed covered lagoon. Water Res 30:843–852

Almond REA, Grooten M, Petersen T, (Eds.). (2020) Living planet report 2020. Bending the curve of biodiversity loss. WWF, Gland

Boyd CE (2013) Assessing the carbon footprint of aquaculture. https://www.Global.seafood.org/advocate/assessing-carbonfootprint-of-aquaculture/. Accessed 10 Jan 2022

Cadman T, Radunsky K, Simonelli A, Maraseni T (2018) From Paris to Poland. Int J Soc Qual 8(2): 27

D'Adamo I, Falcone PM, Morone P (2020) A new socio-economic indicator to measure the performance of bioeconomy sectors in Europe. Ecol Econ 176:106724. https://doi.org/10.1016/j.ecolecon.2020.106724. (FAO, global forum for food and agriculture in 2015)

Dauda AB, Ajadi A, Tola-Fabunmi AS, Akinwole AO (2019) Waste production in aquaculture: sources, components and managements in different culture systems. Aquacult Fisheries 4(3): 81–88. https://doi.org/10.1016/J.AAF.2018.10.002

Edwards P, Pacharaprakiti C, Yomjinda M (1990) Direct and indirect reuse of septage for culture of Nile tilapia (Oreochromis niloticus). Second Asian Fisheries Forum. Asian Fisheries Society, Manila, pp 165–168

FAO (2017) Global livestock environmental assessment model (GLEAM). FAO, Rome, p 109. www.fao.org/gleam/en/

FAO (2020) The state of world fisheries and aquaculture 2020. Sustainability in action. FAO, Rome. https://doi.org/10.4060/ca9229en

FAO, Global Forum for Food and Agriculture (2015). https://www.fao.org/in-action/sustainable-and-circular-bioeconomy/fr/

Galkina NV, Abdullaev DA, Zacharova VL (1965) Biological feed features of duckweeds. (in Russian). Uzb Biol Zh 3:44–47

Galli A, Wiedmann T, Ercin E, Knoblauch D, Ewing B, Giljum S (2012) Integrating ecological, carbon and water footprint into a "footprint family" of indicators: definition and role in tracking human pressure on the planet. Ecol Indic 16:100–112

Gerber PJ, Henderson B, Makkar HP (2013) Mitigation of greenhouse gas emissions in livestock production: a review of technical options for non-CO2 emissions (No. 177). Food and Agriculture Organization of the United Nations (FAO), Rome

Gijzen HJ, Khondker M (1997) An overview of the ecology, physiology, cultivation and applications of duckweed. Inception report. Annex 1. Literature review. Duckweed Research Project (DWRP), Dhaka, p 53

Hagos KW (2012) Survey of resource use efficiency and estimation of carbon and water footprints in fish farming systems using life cycle analysis. University of Rhode Island, Chicago. https://doi.org/10.4060/ca9229en

Haustein AT, Gillman PH, Skillicorn PW, Vergara V, Guevara V, Gastaaduy A et al (1988) Duckweed, a useful strategy for feeding chickens: performance of layers fed with sewage-grown Lemnaceae species. Poult Sci 69:1835–1844

Herzog H, Golomb D (2004) Carbon capture and storage from fossil fuel use. Enc Energy 1 (6562):277–287

Journey WK, Skillicorn P, Spira W (1991) Duckweed aquaculture. Emena Technical Department Agriculture Division, World Bank, Washington, DC

Kanoun-Boule M, Vicente J, Nabais CM, Freitas H (2009) Ecophysiological tolerance of duckweeds exposed to copper. Aquat Toxicol 91(1):1–9

Kardung M, Cingiz K, Costenoble O, Delahaye R, Heijman W, Lovric M et al (2021) Development of the circular bioeconomy: drivers and indicators. Sustainability 13(1). https://doi.org/10.3390/su13010413

Korner S, Vermaat JE (1998) The relative importance of Lemna gibba L., bacteria and algae for the nitrogen and phosphorus removal in duckweed-covered domestic waste water. Water Res 32: 3651–3661

Landesman L, Parker NC, Fedler CB, Konikoff M (2005) Modeling duckweed growth in wastewater treatment systems. Livestock Res Rural Dev 17:61. http://www.lrrd.org/lrrd17/6/land17061.htm. Accessed 4 Nov 2010

Landolt E (1986) Biosystematic investigation on the family of duckweeds: the family of Lemnaceae—a monograph study. Veröffentlichungen des Geobotanischen Institutes ETH, Stiftung Rubel, Zurich

Leng RA (1999) Duckweed: a tiny aquatic plant with enormous potential for agriculture and environment. In: Animal Production and Health Division, University of Tropical Agriculture Foundation, Phnom Penh (Cambodia). FAO, Rome, p 108. http://www.fao.org/ag/AGAinfo/resources/documents/DW/Dw2.htm

Leng RA, Stambolie JH, Bell RE (1994) Duckweed a potential high protein feed resource for domestic animals and fish. In: Improving animal production systems based on local feed resources. 7th AAAP Animal Science Congress, pp 100–117

Liu Y, Rosten TW, Henriksen K, Hognes ES, Summerfelt S, Vinci B (2016) Comparative economic performance and carbon footprint of two farming models for producing Atlantic salmon (Salmo salar): land-based closed containment system in freshwater and open net pen in seawater. Aquacult Eng 71:1–12. https://doi.org/10.1016/j.aquaeng.2016.01.001

Lynd LR, Bothast RJ, Wyman DE (1991) Fuel ethanol from cellulosic biomass. Science 251:1318–1132

MacLeod MJ, Hasan MR, Robb DH, Mamun-Ur-Rashid M (2020) Quantifying greenhouse gas emissions from global aquaculture. Sci Rep 10(1):1–8

Nahar K (2011) Sweet sorghum: an alternative feedstock for bioethanol. Iran J Energy Environ 2(1):58–61

Osmundsen TC, Amundsen VS, Alexander KA, Asche F, Bailey J, Finstad B et al (2020) The operationalisation of sustainability: sustainable aquaculture production as defined by certification schemes. Glob Environ Chang 60:102025. https://doi.org/10.1016/j.gloenvcha.2019.102025

Ren H, Jiang N, Wang T, Omar MM, Ruan W, Ghafoor A (2018) Enhanced biogas production in the duckweed anaerobic digestion process. J Energy Resour Technol 140(4):041805. https://doi.org/10.1115/1.4039782

Russoff LL, Gant DT, Williams DM, Gholson JH (1977) Duckweed a potential feedstuff for cattle. J Dairy Sci 60:161

Skillicorn P, Spira W, Journey W (1993) Duckweed aquaculture—a new aquatic farming system for developing countries. The World Bank, Washington, DC, p 76

Sunny SA (2017) Systemic emergence under transitional uncertainty: the dynamic role of energy technology innovation. Kybernetes 46(9):1527–1541

Verdegem MCJ, Bosma RH (2009) Water withdrawal for brackish and inland aquaculture, and options to produce more fish in ponds with present water use. Water Policy 11(S1):52–68

Wackernagel M, Rees W (1998) Our ecological footprint: reducing human impact on the earth, vol 9. New Society Publishers, Gabriola Island, BC

Williams AS (2009) Life cycle analysis: a step by step approach. Illinois Sustainable Technology Center, Champaign, IL

Wyman CE (1994) Ethanol from lignocellulosic biomass: technology, economics, and opportunities. Bioresour Technol 50:3–6

Xue Y, Zhao X, Huang J, Song Y (2014) Chemical forms, subcellular distribution and binding protein components of cadmium in duckweed Lemna Minor L.: recovery from cadmium exposure. Agrochimica 58(1):90–101

Nutraceuticals in Aquaculture: A Prospective Climate Change Adaptation Strategy

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Abstract

The effects of climate change may raise the physiological stress on cultured aquatic animals that increase the probability of disease outbreak and in turn decrease output and profitability to the fish farmers. Climate change also has an impact on the maturation and breeding cycle, embryonic development, larval quality, survival, organelle and cellular level changes that affect the normal growth of fish. In this context, the negative consequences of climate change on aquaculture production should be ameliorated through implementing effective mitigation techniques. Several strategies such as judicial utilization of resources, adopting technological innovations, precision farming practices and dietary intervention through nutraceuticals are being proposed to enhance the aquaculture production. Among the strategies in this arena, nutritional intervention through incorporation of nutraceuticals to mitigating various stresses is the most promising and widely practiced one. A plethora of nutraceuticals including vitamins, minerals, amino acids, fatty acids, nucleotides, carotenoids, probiotics, microbial products, and phytochemicals are being evaluated globally by several researchers to reduce stress, enhance immunity and growth performance in various commercially important fin and shell fishes. This chapter deals the impact of climate change on aquaculture practice and effective stress mitigation strategy through dietary intervention of nutraceuticals to ensure nutritional security through sustainable aquafarming.

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Keywords

Nutraceuticals · Aquaculture · Climate change · Stress · Adaptation · Nutritional security

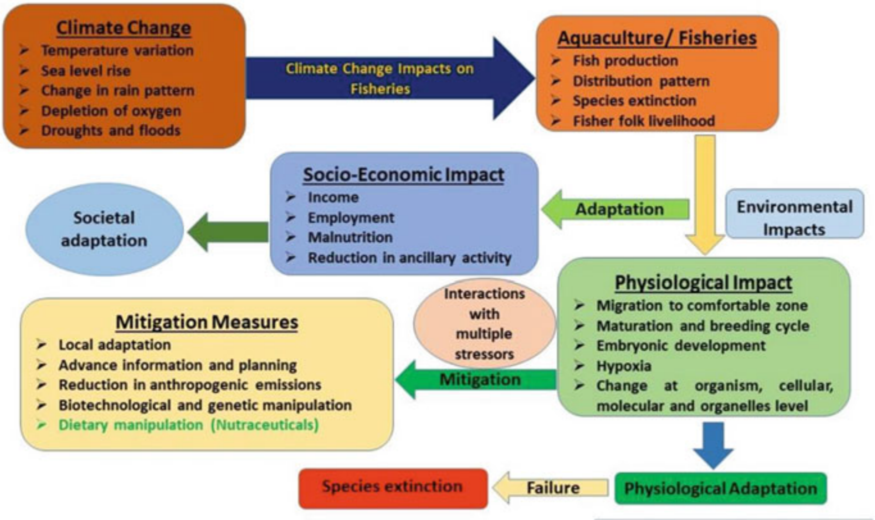
1 Introduction

Climate change is one of the most pressing challenges for humanity. Climate education and research must play an important role in this critical situation. Here, we are attempting to compile some of the most useful information on climate change research that has been generated around the world, with a focus on the impact on fisheries. Aquaculture production has increased by about 12 times in the last three decades, with an average yearly rate of 8.8%. Fish and fishery products are a good source of protein and micronutrients for a well-balanced diet and good health. Fish provided 20% of the average per capita animal protein consumption for more than 3.3 billion people worldwide (FAO 2020). From 1961 to 2017, global food fish consumption attained an annual rate of 3.1%. In 2018, fisheries and aquaculture produced a total of 178.5 million tonnes of fish. Food fish consumption per capita increased by 1.5% each year from 9.0 kg in 1961 to 20.5 kg in 2018. In the first half of this century, global animal protein consumption is predicted to double, reaching over 465 million tonnes of meat and over one billion tonnes of milk. The consumption of farmed fish and chicken is predicted to expand the most. Fish, as the cheapest form of easily digestible animal protein, accounts for a significant portion of the global food basket, and the global fish production sector has the issue of increasing production to fulfill future protein hunger, livelihood, and nutritional security. As a result, the effects of climate change on fish should be highlighted, and effective mitigation techniques should be implemented to reduce the negative consequences.

Fish plays an important part in ensuring food security by delivering protein, vital amino acids, EPA, DHA in fish oils, and essential minerals. Fish consumption is increasing in every country and contributes significantly to the food security of most countries across the world. The domestic need is largely satisfied by aquaculture output, particularly freshwater carp species, in many Asian countries. Fisheries are becoming a more significant part of global food security. Impacts of climate change on the food security sector could affect all four dimensions of food security: availability, stability, access, and usage. Fisheries also contribute significantly to the process of enhancing food security by providing employment opportunities and income to millions of people, as well as aiding in foreign exchange, either directly or indirectly. Those who live in rural areas, notably fishing and fish farming groups, are the most vulnerable to food insecurity. Despite being the principal producers of fish, resource-poor fishing communities continue to be economically disadvantaged in many regions of the world.

2 Impacts on Aquaculture Practices

Aquaculture is an emerging industry, but the effects of climate change are likely to be profound. Climate change may raise physiological stress on cultured animals, which may decrease output and increase disease exposure. It may also put farmers at greater risk and yield lower profits. As a result of direct and indirect influences on natural resources such as water, land, seeds, feed, and energy, aquaculture may have good or negative consequences. Because fisheries require considerable resource inputs, the effects of climate change on these resources will influence aquaculture systems' productivity and profitability. These effects, when combined with other factors such as poverty, inequality, food insecurity, and disease susceptibility, can have a negative influence on communities and limit their ability to adapt. Climate change can have serious consequences for fish physiological processes, adaption mechanisms, and total fisheries. Migration is the deliberate movement of aquatic organisms in pursuit of a more suitable environment. Climate change is projected to produce shifts in species distribution along latitudinal or other climatic gradients. The impacts of climate change on aquaculture/fisheries, in a nutshell, are depicted in Fig. 1.



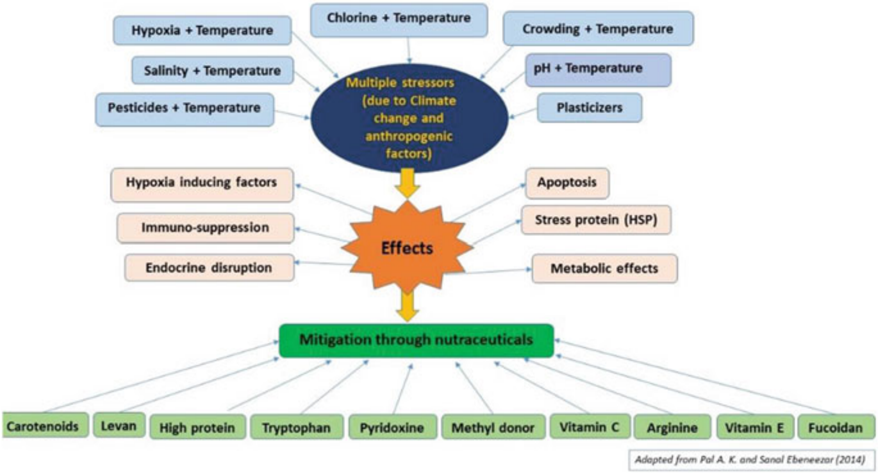
Adapted from Pal A. K. and Sanal Ebeneezar (2014)

Fig. 1 Impact of climate change on aquaculture/fisheries

3 Nutritional Intervention: A Prospective Arena in Climate Change Adaptation

Fish physiology is altered by stressors, which eventually leads to mortality. The stressful condition in fish is caused by a combination of factors such as temperature, crowding, pesticides, heavy metals, acidic and alkaline pH, low dissolved oxygen, and so on. Thermal tolerance, metabolism, food consumption, reproduction, and the ability to maintain internal homeostasis can all be affected by increased temperature. Nutritional intervention or nutraceutical approach to mitigating various stresses in fish is one strategy in this arena. Scientists have continually worked in the field of nutritional intervention for stress management in fish, with positive results. Nutraceuticals have been proved in various studies to activate defense mechanisms in fish, even in stressful situations, and thereby reverse the negative effects mediated by stress. The interactions of multiple stressors, mitigation strategies, and their implications in the context of climate change are represented in Fig. 2.

High protein (50%) and vitamin C (0.2%) supplementation lowers bio-accumulation and stress reactions caused by endosulfan poisoning in *Channa punctatus* and claw ablation stress in *Macrobrachium rosenbergii*. A minimum of 1.36% L-tryptophan supplementation decreased crowding stress and increased growth performance in *Cirrhinus mrigala* fingerlings. L-tryptophan has proven to reduce salinity and heat stress in *L. rohita* juveniles and *Tor putitora* fingerlings. Nutraceuticals not only have stress-relieving properties, but also help to improve heat tolerance. Methyl donors such as choline, betaine, and lecithin have roles in mitigating the negative effects of endosulfan-induced stress. The effects of potential nutraceuticals used in aquaculture are depicted in Table 1.



Adapted from Pal A. K. and Sanal Ebeneezar (2014)

Fig. 2 Nutraceuticals in aquaculture for the mitigation of climate change risks

Table 1 Potential nutraceuticals in aquaculture

Nutraceuticals	Effects	Species	References
Protein and amino acids			
High protein and vitamin C	Stress mitigatory	*Channa punctatus*	Sarma et al. (2009)
		Macrobrachium rosenbergii	Manush et al. (2005)
Tryptophan	Ameliorates thermal stress augments growth and modulates immunity	*Labeo rohita*	Kumar et al. (2014)
	Combating the combined stress of temperature and salinity		Akhtar et al. (2013)
	Mitigating crowding stress and growth augmentation	*Cirrhinus mrigala*	Tejpal et al. (2008)
	Modulates immune status and disease resistance	*Solea senegalensis*	Azeredo et al. (2016a, b)
	Stress mitigation	*Totoaba macdonaldi*	Cabanillas-Gámez et al. (2020)
Glycine	Enhances survival after salinity stress	Oysters	Takeuchi and Gatlin (2007)
Arginine	Improved hypoxia tolerance	*Cirrhinus mrigala*	Varghese et al. (2020a, b)
	Skin wound healing	*Sparus aurata*	Chen et al. (2020)
	Stress mitigation	*Cyprinus carpio*	Hoseini et al. (2019a, b)
Taurine	Stress mitigation, improved growth	*Cyprinus carpio*	Abdel-Tawwab and Monier (2018)
Leucine	Regulates intestinal immune status	*Ctenopharyngodon idella*	Jiang et al. (2015)
Isoleucine	Improved immunity	*Cyprinus carpio*	Zhao et al. (2013)
Glutamine	Reduces inflammation	Rainbow trout	Li et al. (2019)
Methionine	Improves immunity	*Dicentrarchus labrax*	Machado et al. (2020)
Vitamins and minerals			
Vitamin B1	Improves antioxidant defense and inhibits lipid peroxidation and protein oxidation	*Cyprinus carpio*	Li et al. (2014)
	Improved immune response and antioxidative ability	*Trachinotus ovatus*	Xun et al. (2019)

(continued)

Table 1 (continued)

Nutraceuticals	Effects	Species	References
Combination of vitamin C and E	Stress mitigation	*Labeo rohita*	Prusty et al. (2017)
Combination of ascorbic acid and thiamine	Protection against lead toxicity	*Cyprinus carpio*	Mirmazloomi et al. (2015)
Pyridoxine	Stress mitigation, improved thermal tolerance	*L. rohita*	Akhtar et al. (2010, 2012)
Pathothenic acid	Improved growth, intestinal function, and anti-oxidative status	*Megalobrama amblycephala*	Qian et al. (2015)
Folic acid	Enhanced immune and antioxidant parameters	*Megalobrama amblycephala*	Sesay et al. (2016)
	Improved growth performance, immuno-physiological response, and antioxidant status	*Acipenser baerii*	Falah et al. (2020)
Vitamin E	Stress mitigation	*L. rohita*	Ciji et al. (2013a)
	Toxicity amelioration		Kumar et al. (2022)
Vitamin E and L-tryptophan	Improved survival		Ciji et al. (2013b)
	Mitigates hypoxia-mediated oxidative stress	*Cirrhinus mrigala*	Varghese et al. (2017)
Butaphosphan-cyanocobalamin combination	Attenuation of stress	*Paralichthys olivaceus*	Seo et al. (2020)
Myo-inositol	Improved salinity tolerance	*Scophthalmus maximus*	Cui et al. (2020)
		Litopenaeus vannamei	Chen et al. (2018)
Zinc picolinate	Reduction of oxidative stress	Rainbow trout	Kucukbay et al. (2006)
Selenium	Reduced oxidative stress and improved the immune response	*Epinephelus malabaricus*	Lin and Shiau (2007)
	Promoted fish growth and protection against oxidative stress	*Sparus aurata*	Mechlaoui et al. (2019)
	Mitigate the stresses of high temperature and as pollution	*Pangasianodon hypophthalmus*	Kumar et al. (2020)
Nano-selenium	Enhances antioxidant capacity and hypoxia tolerance	*Ctenopharyngodon idella*	Yu et al. (2020)
Magnesium and selenium	Improved growth performance, humoral immunity, and antioxidant capacity	*Lates calcarifer*	Longbaf Dezfouli et al. (2019)
Iron	Reduced oxidative stress and improved the growth	*Heteropneustes fossilis*	Zafar and Khan (2020)

(continued)

Table 1 (continued)

Nutraceuticals	Effects	Species	References
Miscellaneous			
Nucleotides	Reduced levels of serum cortisol Enhanced disease resistance coupled with stress reduction	Rainbow trout	Leonardi et al. (2003)
Bovine lactoferrin	Enhances tolerance to air exposure stress and salinity stress	Orange spotted grouper, *Epinephelus coioides*	Yokoyama et al. (2006)
Glucose and NaCl	Stress mitigation and improved survival	*L. rohita*	Biswal et al. (2020a, b)
GABA (gamma-aminobutyric acid)	Enhanced hypoxia tolerance	*Cirrhinus mrigala*	Varghese et al. (2020a, b)
Microbial levans	Stress mitigatory, protective, and immunostimulant	*Cyprinus carpio*	Gupta et al. (2013)
	Protection against thermal stress	*L. rohita*	Gupta et al. (2010)
Carotenoids	Improved antioxidant status and nonspecific immune responses	*Pangasianodon hypophthalmus*	Gopan et al. (2018)
Picrorhiza kurroa	Anti-stress effect	*Penaeus monodon*	Citarasu et al. (2006)
Phosphatidylserine	Enhanced immunity and antioxidant status	*Penaeus vannamei*	Yang and Pan (2013)
Fucoidan	Enhanced immune response	*L. rohita*	Sajina et al. (2019)
Methyl donors (choline, betaine, and lecithin)	Mitigating the adverse effects of endosulfan and elevated temperature	*L. rohita*	Kumar et al. (2011)
	Mitigating oxidative stress		Muthappa et al. (2013)

4 Conclusion

Fisheries and marine industries are not immune to the whims of climate change. Rising temperatures, increased oxygen consumption, decreased pH, disease risk, sea-level rise pose a major concern for fish and shellfish fisheries. Climate change models estimate a 1–7 °C rise in mean air temperature. Scientists must be ready to confront the difficulties offered by climate change. New candidate species can be identified so that they can better adapt to changing climatic circumstances. Climate changes true impact should be assessed by investigating the synergistic impacts of different stresses on aquatic organisms. A more comprehensive study is required to understand the mechanism of temperature interaction with different stressors. The development of models based on climate change that depict various aquaculture systems is critical for decision-making and cultural practices. Future climate change research should aim to uncover a cause-and-effect knowledge of the underlying mechanisms in biological activities ranging from genome to molecule, cell to tissue, and organism to ecosystem. Various prediction models have been created that might be used to assess the future effects of climate change on fisheries output and food security.

References

Abdel-Tawwab M, Monier MN (2018) Stimulatory effect of dietary taurine on growth performance, digestive enzymes activity, antioxidant capacity, and tolerance of common carp, *Cyprinus carpio* L., fry to salinity stress. Fish Physiol Biochem 44(2):639–649

Akhtar MS, Kumar Pal A, Sahu NP, Ciji A, Kumar N (2012) Effects of dietary pyridoxine on haemato-immunological responses of *Labeo rohita* fingerlings reared at higher water temperature. J Anim Physiol Anim Nutr 96(4):581–590

Akhtar MS, Pal AK, Sahu NP, Ciji A, Meena DK, Das P (2013) Physiological responses of dietary tryptophan fed *Labeo rohita* to temperature and salinity stress. J Anim Physiol Anim Nutr 97(6): 1075–1083

Azeredo R, Machado M, Moura J, Martos-Sitcha J, Mancera J, Peres H, Oliva-Teles A, Afonso A, Costas B (2016a) Dietary tryptophan supplementation modulates immune status and disease resistance in Senegalese sole, *Solea senegalensis*, reared at low or high density. In: Frontiers in Marine Science Conference Abstract: IMMR| International Meeting on Marine Research (Lausanne)

Azeredo R, Machado M, Moura J, Martos-Sitcha J, Mancera J, Peres H, Oliva-Teles A, Afonso A, Costas B (2016b) Dietary tryptophan supplementation modulates immune status and disease resistance in senegalese sole, *Solea senegalensis*, reared at low or high density. In: Paper presented at the international meeting on marine research. Peniche, Portugal

Biswal A, Srivastava PP, Gupta S, Jayant M, Varghese T (2020a) Study on alteration of critical water quality parameters and selected metabolic response of *Labeo rohita* fingerling subjected to transportation stress. J Anim Res 10(4):563–568

Biswal A, Srivastava PP, Jayant M, Varghese T, Gupta S (2020b) Optimisation of transportation condition of *Labeo rohita* fingerling using potential water additives: based on primary and secondary stress responses and survival. J Exp Zool 23(2):1219–1226

Cabanillas-Gámez M, Bardullas U, Galaviz MA, Rodriguez S, Rodriguez VM, López LM (2020) Tryptophan supplementation helps totoaba (*Totoaba macdonaldi*) juveniles to regain homeostasis in high-density culture conditions. Fish Physiol Biochem 46(2):597–611

Chen SJ, Guo YC, Espe M, Yang F, Fang WP, Wan MG, Niu J, Liu YJ, Tian LX (2018) Growth performance, haematological parameters, antioxidant status and salinity stress tolerance of juvenile Pacific white shrimp (*Litopenaeus vannamei*) fed different levels of dietary myo-inositol. Aquacult Nutr 24(5):1527–1539

Chen Z, Ceballos-Francisco D, Guardiola FA, Huang D, Esteban MÁ (2020) Skin wound healing in gilthead seabream (*Sparus aurata* L.) fed diets supplemented with arginine. Fish Shellfish Immunol 104:347–358

Ciji A, Sahu NP, Pal AK, Akhtar MS (2013a) Nitrite-induced alterations in sex steroids and thyroid hormones of *Labeo rohita* juveniles: effects of dietary vitamin E and L-tryptophan. Fish Physiol Biochem 39(5):1297–1307

Ciji A, Sahu NP, Pal AK, Akhtar MS (2013b) Physiological changes in *Labeo rohita* during nitrite exposure: detoxification through dietary vitamin E. Comp Biochem Physiol C Toxicol Pharmacol 158(2):122–129

Citarasu T, Sivaram V, Immanuel G, Rout N, Murugan V (2006) Influence of selected Indian immuno-stimulant herbs against white spot syndrome virus (WSSV) infection in black tiger shrimp, *Penaeus monodon* with reference to haematological, biochemical and immunological changes. *Fish Shellfish Immunol* 21(4):372–384

Cui W, Ma A, Huang Z, Liu Z, Yang K, Zhang W (2020) Myo-inositol facilitates salinity tolerance by modulating multiple physiological functions in the turbot *Scophthalmus maximus*. Aquaculture 527:735451

Falah FJ, Islami HR, Mehrgan MS (2020) Dietary folic acid improved growth performance, immuno-physiological response and antioxidant status of fingerling Siberian sturgeon, *Acipenser baerii* (Brandt 1896). Aquac Rep 17:100391

FAO (2020) The State of World Fisheries and Aquaculture 2020. ISBN: 978-92-5-132692-3. Rome, Italy. Series number: 2020-SOFIA 2020

Gopan A, Ande MP, Varghese T, Sahu NP, Lalappan S, Srivastava PP, Jain KK (2018) Dietary carotenoid supplementation improves fillet appearance, antioxidant status and immune responses in striped catfish (*Pangasianodon hypophthalmus*) nevertheless the growth performance. Turk J Fish Aquat Sci 18(11):1303–1313

Gupta SK, Pal AK, Sahu NP, Dalvi RS, Akhtar MS, Jha AK, Baruah K (2010) Dietary microbial Levan enhances tolerance of *Labeo rohita* (Hamilton) juveniles to thermal stress. Aquaculture 306(1–4):398–402

Gupta SK, Pal AK, Sahu NP, Jha AK, Akhtar MS, Mandal SC et al (2013) Supplementation of microbial Levan in the diet of *Cyprinus carpio* fry (Linnaeus, 1758) exposed to sublethal toxicity of fipronil: effect on growth and metabolic responses. Fish Physiol Biochem 39(6): 1513–1524

Hoseini SM, Vatnikov YA, Kulikov EV, Petrov AK, Hoseinifar SH, Van Doan H (2019a) Effects of dietary arginine supplementation on ureagenesis and amino acid metabolism in common carp (*Cyprinus carpio*) exposed to ambient ammonia. Aquaculture 511:734209

Hoseini SM, Yousefi M, Hoseinifar SH, Van Doan H (2019b) Effects of dietary arginine supplementation on growth, biochemical, and immunological responses of common carp (*Cyprinus carpio* L.), stressed by stocking density. Aquaculture 503:452–459

Jiang WD, Deng YP, Liu Y, Qu B, Jiang J, Kuang SY, Tang L, Tang WN, Wu P, Zhang YA, Zhou XQ (2015) Dietary leucine regulates the intestinal immune status, immune-related signalling molecules and tight junction transcript abundance in grass carp (*Ctenopharyngodon idella*). Aquaculture 444:134–142

Kucukbay Z, Yazlak H, Sahin N, Tuzcu M, Cakmak MN, Gurdogan F, Juturu V, Sahin K (2006) Zinc picolinate supplementation decreases oxidative stress in rainbow trout (*Oncorhynchus mykiss*). Aquaculture 257(1–4):465–469

Kumar N, Jadhao SB, Chandan NK, Kumar K, Jha AK, Bhushan S, Kumar S, Rana RS (2011) Dietary choline, betaine and lecithin mitigates endosulfan-induced stress in *Labeo rohita* fingerlings. Fish Physiol Biochem 38(4):989–1000

Kumar P, Saurabh S, Pal AK, Sahu NP, Arasu ART (2014) Stress mitigating and growth enhancing effect of dietary tryptophan in rohu (*Labeo rohita*, Hamilton, 1822) fingerlings. Fish Physiol Biochem 40(5):1325–1338

Kumar N, Gupta SK, Chandan NK et al (2020) Mitigation potential of selenium nanoparticles and riboflavin against arsenic and elevated temperature stress in *Pangasianodon hypophthalmus*. Sci Rep 10:17883. https://doi.org/10.1038/s41598-020-74911-2

Kumar M, Gupta G, Muhammed NP, Varghese T, Srivastava PP, Bhushan S, Shukla SP, Krishna G, Gupta S (2022) Toxicity ameliorative effect of vitamin E against super-paramagnetic iron oxide nanoparticles on haemato-immunological responses, antioxidant capacity, oxidative stress, and metabolic enzymes activity during exposure and recovery in *Labeo rohita* fingerlings. Aquac Int:1–29

Leonardi M, Sandino AM, Klempau A (2003) Effect of a nucleotide-enriched diet on the immune system, plasma cortisol levels and resistance to infectious pancreatic necrosis (IPN) in juvenile rainbow trout (*Oncorhynchus mykiss*). Bull Eur Assoc Fish Pathol 23(2):52–59

Li XY, Huang HH, Hu K et al (2014) The effects of dietary thiamin on oxidative damage and antioxidant defence of juvenile fish. Fish Physiol Biochem 40:673–687. https://doi.org/10.1007/s10695-013-9875-6

Li S, Guo Q, Li S, Zheng H, Chi S, Xu Z, Wang Q (2019) Glutamine protects against LPS-induced inflammation via adjusted NODs signaling and enhanced immunoglobulins secretion in rainbow trout leukocytes. Dev Comp Immunol 98:148–156

Lin Y-H, Shiau S-Y (2007) The effects of dietary selenium on the oxidative stress of grouper, *Epinephelus malabaricus*, fed high copper. Aquaculture 267(1–4):38–43. https://doi.org/10.1016/j.aquaculture.2006.12.015

Longbaf Dezfouli M, Ghaedtaheri A, Keyvanshokooh S, Salati AP, Mousavi SM, Pasha-Zanoosi H (2019) Combined or individual effects of dietary magnesium and selenium nanoparticles on growth performance, immunity, blood biochemistry and antioxidant status of Asian seabass (*Lates calcarifer*) reared in freshwater. Aquacult Nutr 25(6):1422–1430

Machado M, Engrola S, Colen R, Conceição LE, Dias J, Costas B (2020) Dietary methionine supplementation improves the European seabass (*Dicentrarchus labrax*) immune status following long-term feeding on fishmeal-free diets. Br J Nutr 124(9):890–902

Manush SM, Pal AK, Das T, Mukherjee SC (2005) Dietary high protein and vitamin C mitigate stress due to chelate claw ablation in *Macrobrachium rosenbergii* males. Comp Biochem Physiol A Mol Integr Physiol 142(1):10–18

Mechlaoui M, Dominguez D, Robaina L, Geraert PA, Kaushik S, Saleh R, Briens M, Montero D, Izquierdo M (2019) Effects of different dietary selenium sources on growth performance, liver and muscle composition, antioxidant status, stress response and expression of related genes in gilthead seabream (*Sparus aurata*). Aquaculture 507:251–259

Mirmazloomi S, Shahsavani D, Baghshani H (2015) Studies on the protective effects of ascorbic acid and thiamine on lead-induced lipid and protein oxidation as well as enzymatic alterations in some tissues of *Cyprinus carpio*. Comp Clin Pathol 24(5):1231–1236

Muthappa NA, Gupta S, Yengkokpam S, Debnath D, Kumar N, Pal AK, Jadhao SB (2013) Lipotropes promote immunobiochemical plasticity and protect fish against low-dose pesticide-induced oxidative stress. Cell Stress Chaperones 19(1):61–81

Prusty AK, Sahu NP, Mohapatra S (2017) Immuno-stimulating impacts of dietary enrichment of vitamin C and E combinations in Labeo rohita Fingerlings. Prog Agric 17(1):26–32. https://doi.org/10.5958/0976-615.2017.00032.1

Qian Y, Li XF, Zhang DD, Cai DS, Tian HY, Liu WB (2015) Effects of dietary pantothenic acid on growth, intestinal function, anti-oxidative status and fatty acids synthesis of juvenile blunt snout bream *Megalobrama amblycephala*. PLoS One 10(3):e0119518

Sajina KA, Sahu NP, Varghese T, Jain KK (2019) Fucoidan-rich Sargassum wightii extract supplemented with α-amylase improve growth and immune responses of *Labeo rohita* (Hamilton, 1822) fingerlings. J Appl Phycol 31(4):2469–2480

Sarma K, Pal AK, Sahu NP, Ayyappan S, Baruah K (2009) Dietary high protein and vitamin C mitigates endosulfan toxicity in the spotted murrel, *Channa punctatus* (Bloch, 1793). Sci Total Environ 407(12):3668–3673

Seo JS, Lee JH, Park JJ, Choi JS, Bae JS, Lee CW, Yang CY, Kang YJ, Choi SH, Park KH (2020) Biochemical and stress-attenuating effects of butaphosphan-cyanocobalamin combination drug in olive flounder *Paralichthys olivaceus*. Fish Sci 86(2):375–384

Sesay DF, Habte-Tsion HM, Zhou Q, Ren M, Xie J, Liu B, Chen R, Pan L (2016) Effects of dietary folic acid on the growth, digestive enzyme activity, immune response and antioxidant enzyme activity of blunt snout bream (*Megalobrama amblycephala*) fingerling. Aquaculture 452:142–150

Takeuchi T, Gatlin DM III (2007) Amino acids, peptides. In: Dietary supplements for the health and quality of cultured fish. CAB International, Wallingford, pp 47–63

Tejpal CS, Pal AK, Sahu NP, Kumar JA, Muthappa NA, Vidya S, Rajan MG (2008) Dietary supplementation of L-tryptophan mitigates crowding stress and augments the growth in *Cirrhinus mrigala* fingerlings. Aquaculture 293(3–4):272–277

Varghese T, Pal AK, Sahu NP, Mishal P, Dasgupta S (2017) Effects of hypoxia and dietary vitamin E on growth performance and oxidative status of *Cirrhinus mrigala* (ham., 1822). Anim Biol 67(2):133–148

Varghese T, Kumar VR, Gopan A, Valappil RK, Sajina KA, Mishal P, Pal AK (2020a) Dietary arginine modulates nonspecific immune responses in Indian major carp, *Cirrhinus mrigala* exposed to hypoxia. Aquaculture 529:735613

Varghese T, Rejish Kumar VJ, Anand G, Dasgupta S, Pal AK (2020b) Dietary GABA enhances hypoxia tolerance of a bottom-dwelling carp, *Cirrhinus mrigala* by modulating HIF-1α, thyroid hormones and metabolic responses. Fish Physiol Biochem 46(1):199–212

Xun P, Lin H, Wang R, Huang Z, Zhou C, Yu W, Huang Q, Tan L, Wang Y, Wang J (2019) Effects of dietary vitamin B1 on growth performance, intestinal digestion and absorption, intestinal microflora and immune response of juvenile golden pompano (*Trachinotus ovatus*). Aquaculture 506:75–83

Yang L, Pan L (2013) Effects of phosphatidyl serine on immune response in the shrimp *Litopenaeus vannamei*. Cent Eur J Biol 8(11):1135–1144

Yokoyama S, Koshio S, Takakura N, Oshida K, Ishikawa M, Gallardo-Cigarroa FJ, Catacutan MR, Teshima SI (2006) Effect of dietary bovine lactoferrin on growth response, tolerance to air exposure and low salinity stress conditions in orange spotted grouper *Epinephelus coioides*. Aquaculture 255(1–4):507–513

Yu H, Zhang C, Zhang X, Wang C, Li P, Liu G, Yan X, Xiong X, Zhang L, Hou J, Liu S (2020) Dietary nano-selenium enhances antioxidant capacity and hypoxia tolerance of grass carp *Ctenopharyngodon idella* fed with high-fat diet. Aquacult Nutr 26(2):545–557

Zafar N, Khan MA (2020) Effects of dietary iron on growth, haematology, oxidative stress and hepatic ascorbic acid concentration of stinging catfish *Heteropneustes fossilis*. Aquaculture 516: 734642

Zhao J, Liu Y, Jiang J, Wu P, Jiang W, Li S, Tang L, Kuang S, Feng L, Zhou X (2013) Effects of dietary isoleucine on the immune response, antioxidant status and gene expression in the head kidney of juvenile Jian carp (*Cyprinus carpio* var. Jian). Fish Shellfish Immunol 35(2):572–580

Part IV

Strategies and Planning on Reproductive Physiology and Feed Management for Biodiversity Conservation

Broodstock Development, Induced Breeding, and Seed Production of Climbing Perch *Anabas testudineus*: An Alternative Aquaculture Species for Changing Environment

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Abstract

The climbing perch, *Anabas testudineus* is one of the potential air-breathing species with high commercial value and consumer preferences. It is a highly preferred food fish in Southeast Asian countries and fetches high market prices (₹300–500/kg). The fish contains a high amount of physiologically available iron and copper which is essential for hemoglobin synthesis. Owing to its importance the ICAR-CIFA, Bhubaneswar has developed the technology of seed production and grow-out culture of climbing perch. Broodstock can be raised in the earthen pond (0.02–0.05 ha) or even in concrete tanks (15–20 m^2). The mature brooders are selected based on the secondary sexual characters for the induced breeding trials. Mature females exhibit bulged abdomen, prominent outgrowth at the vent in the form of the genital papilla, and oozing of ova even at a gentle pressure on the abdomen. Mature males appear slender and smaller in size and have longer anal fins than females and gentle pressure on the abdomen oozes out white milt. The inducing hormone (OVATIDE/WOVA-FH/GONOPROFH) is injected intramuscularly in females and males @ 0.5–1.0 and 0.25–0.5 μL/g body weight, respectively. The hormone-injected fishes are released into the breeding pool with stagnant water and take 7–8 h to spawn. The average fecundity is about 300–400 eggs/g bodyweight of the female. The time duration from spawning to hatching is about 12–15 h at a water temperature range of 28–30 °C. Climbing perch spawn takes 3 days to absorb yolk sac and feeding starts from the fourth day with microzooplankton, especially rotifers. Plankton feeding should be given for 10–15 days and then it can be supplemented with formulated powdered feed (500–700 μ) having 42–45% protein. In 3 weeks time, the fry grows to a size of 20–25 mm and they are fed with supplemented feed consisting of rice bran,

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soybean flour, GNOC, and fishmeal with a protein level of 35%. Fry becomes fingerlings in 1 month and grows to an average size of 1.50–2.0 5 g with 70–75% survival. Climbing perch, at their early life stages, exhibit partial cannibalism and therefore, shooters to be segregated and raised with similar-sized individuals for better survival of climbing perch seed.

Keywords

Climbing perch · Broodstock development · Captive breeding · Seed Production · *Anabas testudineus* · Cannibalism

1 Introduction

Indian aquaculture production mainly depends on carp, but the utilization of floodwater and derelict water in a scientific manner for different culture systems and the selection of proper species would definitely add to the food basket as well as entrepreneurship and employment generation. Air-breathing fish shows tremendous potential to enhance production in derelict and neglected swampy water bodies. The climbing perch, *Anabas testudineus* is an air-breathing species with high economic value and consumer preference. It is popularly known as Kavai or Koi. This is an organoleptically favored fish and fetches better market prices in several states like Assam, Tripura, West Bengal, Bihar, Manipur, Kerala, and Jharkhand (Kumar et al. 2013a). The fish contains a high amount of physiologically available Fe and Cu essential for hemoglobin synthesis and is also rich in unsaturated fatty acids (Kumar et al. 2013b). Despite its nutritive value and availability in the live condition its farming practice has not received much attention mainly due to the non-availability of packages of practices for seed production, difficulty in larval rearing, and growing out technology (Kumar et al. 2012a). The ICAR-Central Institute of Freshwater Aquaculture, Bhubaneswar has standardized the seed production and culture technologies and disseminated them to the different stakeholders of the country which helped in the spread of farming in the country. In the past few years due to the advent of biofloc, aquaponics systems, and RAS technology, climbing perch farming has grown speedily in the peri-urban areas which are mainly due to tolerance of oxygen stress and suitable for farming in high density (Anantharaja et al. 2017). Since the climbing perch can tolerate adverse environmental conditions and therefore, it is being considered one of the most important fish species for climate-resilient aquaculture (Das et al. 2019) (Fig. 1).

2 Natural Distribution and Biology

The climbing perch's natural range of distribution is Eastern and Southeast Asia (Talwar and Jhingran 1991). It lives in rivers, canals, stagnant water bodies, swamps, trenches, paddy fields, streams, and estuaries (Pethiyagoda 1991; Talwar and

Fig. 1 Climbing perch adult

Jhingran 1991). Its possession of accessory air-breathing organs allows it to subsist for many days out of the water when the air-breathing organs are kept moist. Fishes are caught from the wild and also cultivated in ponds/cages/tanks and they are sold by being kept in baskets under moist conditions (Axelrod et al. 1971). In the dry season, it remains buried under the mud. It has a popularity for its ability to crawl using its operculum and pectoral fins on land for some distance. Migration is most common at night and after the rain. This lateral migration helps the fish to travel from the mainstream, or other natural water bodies, to inundated areas in the monsoon season. It is considered a hardy species. Climbing perch occurs in fresh as well as in brackish waters (Sterba 1983; Riehl and Baensch 1991). The air-breathing ability and tolerance to a wide range of unfavorable environmental conditions make the species a suitable species for culture in neglected water bodies and derelict ponds which are not suitable for carp culture.

The climbing perch is a teleost belonging to the family Anabantidae and order Perciformes. It has an elongated and moderately deep body with a broad head and a compressed body. The abdomen and pectoral and anal fins are pale yellow-colored (Zworykin 2012) and at the caudal fin base, a dark spot is present. As a distinguishing mark, a dark spot is found just behind the gill plate and another at the caudal base. The scales and fins' edges are brightly colored and have serrated opercula and preopercle. The teeth are villiform and the mouth is fairly large. It bears accessory respiratory organs, and one pair of labyrinthine and respiratory membranes within the suprabranchial chamber, which enable them to breathe atmospheric air (Sakurai et al. 1993). The accessory respiratory organ develops during the larval stage; labyrinthine organs start to develop on the fifth day after hatching but, air-breathing does not occur until the 13th–14th day (Maina 2002). It is sexually dimorphic, but the dimorphism generally occurs with the approach of the breeding season (Banerji and Prasad 1974; Dehadrai et al. 1973).

3 Broodstock Management

Contrary to other anabantids, climbing perch do not show parental care and nest-making behavior (Axelrod et al. 1971; Sakurai et al. 1993). It attains maturity in the 5–6 months itself when it attains the size of 14–18.2 g/8.0–9.2 cm. Its breeding starts from March and lasts till late August with a peak in the monsoon season. Male and females develop their notable secondary sexual character during the breeding season. Mature females display bulged abdomen, prominent outgrowth at the vent in the form of the genital papilla, and oozing of ova even at gentle pressure on the abdomen. Mature males appear slender and smaller in size and have longer anal fins than females and gentle pressure on the abdomen oozes out white milt. Broodstock can be raised in the earthen pond (0.02–0.05 ha) or even in concrete tanks (15–20 m^2). The raising of brooders in concrete tanks gives the advantage of better management and easy brood collection during induced breeding. Water exchange is done weekly @ 20–30% of total water volume (Kumar et al. 2012b). The physico-chemical parameters of the tank such as dissolved oxygen (DO), free CO_2, pH, alkalinity, and NH_3 are recorded fortnightly. Brood fishes are fed with a supplementary diet (30–35% protein) @ 3–4% of the fish biomass per day. Monthly sampling was carried out to monitor the health and the progress of maturity. The progress of maturity was assessed based on abdominal bulging and change in vent appearance in the case of the female, whereas the mature male was distinguished on the basis of the oozing milt on applying slight pressure alongside the abdomen (Sarkar et al. 2005). Fully mature fishes are taken for induced breeding (Figs. 2 and 3).

4 Captive Breeding

The mature brooders are selected based on the secondary sexual characters for the induced breeding trials. The females and males are intramuscularly injected with inducing hormone (OVAPRIM/OVATIDE/WOVA-FH/GONOPROFH) @ 0.5–1.0

Fig. 2 Climbing perch broodstock

Fig. 3 Climbing perch mature female and male

and 0.25–0.5 μL/g body weight, respectively. The injected fishes are released into the breeding pool with stagnant water. Since it lays free-floating eggs there is no need for unnecessary water circulation in the breeding pool. After 7–8 h of hormonal injection, fishes spawn in the tanks. The pelagic fertilized eggs are small, circular, and transparent. The fertilized eggs are small ranging between 0.80 and 0.90 mm in diameter after water hardening and float on the water surface. They appeared like non-adhesive tiny crystal beads. The fertilized eggs look transparent, but the unfertilized eggs look opaque or milky. Fecundity is about 300–400 eggs/g bodyweight of the female. The fertilized eggs are hatched in stagnant water in FRP tanks (500–1000 L) with a stocking density of 3–4 fertilized eggs per liter of water. The time duration from spawning to hatching is about 12–15 h at a water temperature range of 26–28 °C. The unfertilized eggs make clumps on the surface of the water and that should be removed, which otherwise allows the spread of bacterial/fungal growth and thereby chances of infections to the spawn. Hatched spawns are allowed to remain in the same tanks for further rearing up to the fry stage (Mandal et al. 2016).

Generally, a fish breeds once a year in nature, and the breeding season lasts from May to August. Attempts were made to breed the same fish several times in the same year during the annual reproductive cycle, to meet the growing demand for seeds. In ICAR-CIFA the multiple spawning, as well as offseason breeding of this fish, has been carried out with proper diet and water quality management. The offseason breeding of this species in the first week of December has paved the way for round-

Fig. 4 Climbing perch eggs

Fig. 5 Floating eggs with brooders after spawning

the-year production of quality seed. Thus adopting this method, the stakeholders can improve the seed availability for stocking and also for commercial purposes (Figs. 4 and 5).

5 Fry and Fingerlings Rearing

The newly hatched larvae measure 1.6–1.8 mm in length and rest in the upside-down position. Climbing perch spawn takes 3 days to absorb yolk sac and feeding starts from the fourth day with microzooplankton, especially rotifers. The monoculture of rotifers is preferred but if not there then planktons are collected from the well-fertilized ponds with plankton nets and they are filtered out through a fine filter cloth to obtain smaller rotifers. After 4–5 days of rearing moina can be given and after 7 days copepods may also be used. Plankton feeding should be given for 10–15 days and then it can be supplemented with formulated powdered feed (500–700 μ) having 42–45% protein. After 1 month, it is fed with rice bran and oil cake in moist

Fig. 6 Climbing perch seed

condition or commercially available pelleted feed having 40% protein. Fishes are raised in indoor rearing tanks of 500–1000 L capacity with a water depth of 15–20 in. To get better survival, the systematic water exchange, feeding, and thinning of hatchlings are essential. A stocking density of 1000–1500/m^2 is ideal for the initial 15 days for higher growth and survival under indoor conditions. In 2 weeks, spawn reaches the size of 12–16 mm.

In 3 weeks time, the fry grows to 20–25 mm and they are fed with supplemented feed consisting of rice bran, soybean flour, GNOC, and fishmeal with a protein level of 35%. Size heterogeneity is common in climbing perch seed rearing and it leads to cannibalism. Generally, partial cannibalism is seen in climbing perch, and shooters attack weaker individuals. Therefore, regular segregation of shoot fry (bigger fish) is done and reared separately. The concrete tank fry rearing with low water depth (75 cm) results in better survival. Fry is reared @ 250–300 fry/m^2. Fry is fed with formulated floating feed containing 35% protein. Fry becomes fingerlings in 1 month. In 1 month of culture, they grew to an average size of 1.50–2.0 5 g/ 3.70–4.10 cm with 70–75% survival. Fingerling is also fed with either formulated floating feed or rice bran and oil cake dough (Fig. 6).

6 Cannibalism and Its Management During Seed Rearing

Fishes exhibit cannibalism more commonly than in any other animal taxa (Naumowicz et al. 2017). Climbing perch, at their early life stages, exhibit partial cannibalism. The risk of secondary infection is always very high as partial cannibalism provides an opportunity for the pathogen to proliferate in open wounds. Cannibalism cannot be removed fully because it is a genetically inherited trait. However, it can be disguised partially through the stocking density, diet, domestication, and environmental interventions in the climbing perch seed rearing. Cannibalism can also be reduced by avoiding significant size heterogeneities within the population in the nursery rearing of climbing perch (Das et al. 2019). Regular size sorting of young ones in carnivorous fishes is essential during the nursery rearing to minimize the incidence of cannibalism (Kumari et al. 2018). Therefore, shooters to be segregated and raised with similar-sized individuals for better survival of climbing perch seed. Das et al. (2019) reported a reduced cannibalism rate and increased growth and survival during climbing perch fry rearing when fed @ 6% of the body weight with a feeding frequency of 4 times a day.

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References

Anantharaja K, Mohapatra BC, Pillai BR, Kumar R, Devaraj C, Majhi D (2017) Growth and survival of climbing perch, *Anabas testudineus* in nutrient film technique (NFT) aquaponics system. Int J Fish Aquat Stud 5(4):24–29

Axelrod HR, Emmens CW, Sculthorpe D, Winkler WV, Pronek N (1971) Exotic tropical fishes. TFH Publications, Jersey City, NJ

Banerji SR, Prasad D (1974) Observations on reproduction and survival of Anabas testudineus (Bloch) in Bihar region. J Inland Fish Soc 6:6–17

Das L, Rajesh K, Mohanta KN, Mohanty UL, Pillai BR, Sundaray JK (2019) Effect of feeding frequency on growth, feed utilisation and cannibalism in climbing perch Anabas testudineus (Bloch 1792) fry. Indian J Fisheries 66(1):106–111

Dehadrai PV, Banerjee SR, Thakur NK, Das NK (1973) Sexual dimorphism in certain air-breathing teleost. Inland Fish Soc India 15:71–78

Kumar K, Kumar R, Mohanty UL, Saurav S, Sahoo M, Mohanty AK, Sahu AK, Jayasankar P (2012a) Climbing perch, *Anabas testudineus*: consumer delicacy. Fishing Chimes 32(6):40–44

Kumar K, Mohanty U, Kumar R, Damle D, Jahan N, Jena JK, Eknath AE (2012b) Aquac Asia 17(3):27–28

Kumar K, Sarma S, Chakrabarti PP, Kumar R, Mohanty UL, Sahoo M, Mohanty AK, Sahu AK, Jayasankar P (2013a) *Anabas* (koi) farming in Sonapur, Assam, a successful demonstration. Fishing Chimes 33(1 & 2):136–137

Kumar K, Lalrinsanga PL, Sahoo M, Mohanty UL, Kumar R, Sahu AK (2013b) Length-weight relationship and condition factor of *Anabas testudineus* and *Channa* species under different culture systems. World J Fish Mar Sci 5:74–78

Kumari S, Tiwari VK, Rani AMB, Kumar R, Praksah S (2018) Effect of feeding rate on growth, survival and cannibalism in striped snakehead, Channa striata (Bloch, 1793) fingerlings. J Exp Zool India 21:205–210

Maina JN (2002) Structure, function and evolution of the gas exchangers: comparative perspectives. J Anat 201(4):281–304

Mandal B, Kumar R, Jayashankar P (2016) Efficacy of exogenous hormone (GnRHa) for induced breeding of climbing perch (*Anabas testudineus)* and influence of operational sex ratio on spawning success. Anim Reprod Sci 171:114–120. https://doi.org/10.1016/j.anireprosci.2016.06.006

Naumowicz K, Pajdak J, Terech-Majewska E, Szarek J (2017) Intracohort cannibalism and methods for its mitigation in cultured freshwater fish. Rev Fish Biol Fish 27:193–208. https://doi.org/10.1007/s11160-017-9465-2

Pethiyagoda R (1991) Freshwater fishes of Sri Lanka. The Wildlife Heritage Trust of Sri Lanka, Colombo, p 362

Riehl R, Baensch HA (1991) Aquarium Atlas. Mergus, Melle, p 992

Sakurai A, Sakamoto Y, Mori F (1993) In: Loiselle PV (ed) Aquarium fish of the world: the comprehensive guide to 650 species. English translation by Takeshi Shimizu with Neil M. Teitler. Chronicle Books, San Francisco, p 288

Sarkar UK, Deepak PK, Kapoo D, Negi RS, Paul SK, Singh S (2005) Captive breeding of climbing perch *Anabas testudineus* (Bloch, 1792) with Wova-FH for conservation and aquaculture. Aquacult Res 36(10):941–945. https://doi.org/10.1111/j.1365-2109.2005.01281.x

Sterba G (1983) The aquarium fish encyclopedia. The MIT Press, Cambridge, MA, p 605

Talwar PK, Jhingran AG (1991) Inland fishes of India and adjacent countries, vol 2. CRC, Boca Raton, FL

Zworykin DD (2012) Reproduction and spawning behavior of the climbing perch *Anabas testudineus* (Perciformes, Anabantidae) in an aquarium. J Ichthyol 52(6):379–388

Effect of Changing Environmental Factors on Reproductive Cycle and Endocrinology of Fishes

Prem Kumar, M. Babita, M. Kailasam, M. Muralidhar, T. Hussain, A. Behera, and K. P. Jithendran

Abstract

Biological rhythms in animals are coordinated by external environmental factors. In teleost, the reproductive cycle is synchronized with seasonal changes in the climate. This synchronization is to ensure the maximum survival of young ones. The reproductive cycle in fish is under the control of the brain–pituitary–gonad (BPG) axis. BPG axis is regulated by external environmental factors. Some environmental stimuli trigger the release of gonadotropin-releasing hormone (GnRH) from the hypothalamus of the brain, which regulates the recreation of gonadotropin (follicle-stimulating hormone, FSH, and luteinizing hormone, LH) from the pituitary gland. FSH regulates the gonad development and LH regulates the final maturation and spawning. Environmental factors such as temperature, photoperiod, rainfall, and other physico-chemical parameters of water (dissolved oxygen, water temperature, salinity, hardness, pH, etc.) influence fish reproduction and breeding. Due to global climate change and global warming all these environmental factors are fluctuating, which influences the maturation, migration, spawning, development, sex ratio, and survival of the new recruits. The current review is focused on the effect of important environmental changes (stress), lunar cycle, and photoperiod on the fish reproductive cycle.

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Keywords

Breeding · Gonad development · Reproductive cycle · Environmental factors · Climate change

1 Introduction

Reproductive endocrinology of teleost is regulated by external environmental conditions. The biological rhythms in animals are coordinated by external factors. In fish, the timing of developmental and maturational events is synchronized with seasonal changes in climate, day length, and food supply. This coordination between reproduction and environment is to ensure the survival of a young one in the most ideal environment. Fish of temperate zones mature and spawn when temperatures and day length are high in the spring. In the subtropical and tropical zones, reproductive development and spawning occur during the rainy season. Therefore, the number of environmental factors such as temperature, photoperiod, rainfall, and other water qualities (dissolved oxygen, salinity, hardness, pH, etc.) influence fish reproduction and breeding. Due to global climate change, many environmental parameters are fluctuating and influencing reproductive physiology and breeding of fish. Therefore, it is important to understand the impact of changing environment on fish breeding and reproductive adaptation by fishes.

2 Fish Endocrinology and Breeding

Fish species are more than half of all vertebrate that is widely adapted to both marine and freshwater ecosystem (Nelson and Sheridan 2006). The reproductive cycle of fish is divided into two phases. In phase one gametic cell grows, proliferates, and differentiates to gametes (spermatogenesis and oogenesis) and the second phase includes the final maturation release of germ cells. Both phases are controlled by the brain–pituitary–gonad (BPG) axis. Environmental stimuli trigger the release of gonadotropin-releasing hormone (GnRH) from the hypothalamus of the brain, which regulates the recreation of gonadotropin (follicle-stimulating hormone, FSH, and luteinizing hormone, LH) from the pituitary gland. In some fishes (mostly freshwater fish) during unfavorable or captive condition dopamine is released from the hypothalamus which inhibits the release of LH and stops the final oocyte maturation and spawning in farmed/captive condition (Kumar et al. 2022). FSH and LH regulate the production of sex steroids (androgens, estrogens, and progestogens). These sex steroids regulate gonadal development. FSH induces steroidogenesis in a two-cell model in which outer theca cells synthesize testosterone (T), which move to granulosa cells to synthesize 17β-estradiol (E2) by P-50 aromatase (Montserrat et al. 2004). The E2 regulates vitellogenesis in liver and oocyte development. FSH also helps to incorporate vitellogenin (Vtg) into the oocyte (Jalabert 2005). LH triggers the synthesis and secretion of maturation-inducing hormone (MIH) or maturation-inducing steroids (MIS) in follicle cells, which regulate final oocyte maturation and ovulation in females and spermiation in males (Nagahama et al. 1994; Suwa and Yamashita 2007). A change in steroidogenesis occurs from E2 synthesis to dihydroxy progesterone (DHP) or 20β-S in fish ovarian follicles under the control of LH (Nagahama and Yamashita 2008). The first induced breeding (final oocyte maturation and ovulation) in fish was recorded by Houssay in 1930, which is known as hypophysation technique. In this technique, pituitary gland extracts are used to induce spawning in fish (Von Ihering 1937). The most commonly used inducing agents in fish breeding are pituitary gland extract (PGE), human chorionic gonadotropin (HCG), and the mixture of synthetic GnRH analog and dopamine antagonist (DA). Pituitary gland extract of mature fish (carp and salmonids) during the reproductive season contains high amounts of LH, which act directly on gonad and stimulate ovulation and spawning. It has some drawbacks: (a) change in LH concentration in the pituitary, (b) other hormones present in the pituitary may affect adversely, and (c) there is a chance of transfer of disease from the donor to recipient fish. Purified HCG directly acts on gonads and stimulates ovulation and spawning (Zohar and Mylonas 2001). The commercial approved HCG for aquaculture use is CHORULONTM (Intervet International bv, Netherlands). Generally, a dose of HCG ranged between 100 and 4000 international units (IU) per kg body weight. Compared to pituitary gonadotropin HCG has a longer half-life in blood circulation. Use of GnRH (GnRHa) is widely used due to its advantages over the preparation of LH: (a) GnRHa is more species-specific, (b) the chance of disease transmission is less, (c) it acts at a higher level of the brain–pituitary–gonad axis and thus gives good integration of reproductive events. The commercially approved GnRHa in aquaculture is Azagly-nafarelin (GONAZONTM, Intervet International bv, The Netherlands). In some fish inhibitory role of dopamine on the release of LH is prominent. Therefore, the use of DA antagonists (e.g., domperidone, pimozide, reserpine, or metoclopramide) enhances the stimulatory effect of GnRHa on LH release. Many commercial fish breeding hormone is prepared by pharma industries with the almost similar chemical formulation.

3 Impact of Climate Change on Aquatic Environment

Since the century, the average global temperature of the earth and frequent uneven climate events are intensified (Brander 2010). This is a well-known phenomenon of global warming, which increases the temperature of the water ecosystem (Ficke et al. 2007). Human activities have produced amassed releases of carbon dioxide (CO_2) and other greenhouse gases. During the last 40 years, the CO_2 level in the atmosphere has increased from 78 to 400 parts per million (ppm) (Bopp et al. 2013). This raise has altered the environment of different ecosystems. The effect of climate change will be more intense on land. The extreme weather events on land will influence mainly change in water salinity, flow, and temperature. An increase in runoff and flood will change the water turbidity and light penetration into the water column which will change the productivity and other biochemical processes in water. Changes in water flow will also influence the movement of fish migration, which is associated with the physiology and reproduction of fish. Due to the ectothermic nature of fish, the water temperature will influence fish physiology. Global climate is regulated by the continuous exchange of heat between the atmosphere and earth, which influences ocean temperature. Due to this, sea level and seawater temperature raise (Bopp et al. 2013; Church et al. 2013). The rise in sea level will change the salinity of seawater in the polar regions. Atmospheric CO_2 gets stored in the ocean, which drops in ocean surface pH, which is popularly known as acidification (Gattuso et al. 2015).

Ocean temperature reduces the dissolved oxygen (DO) in the ocean. This happened due to the poor solubility of O_2 at high water temperatures. Higher ocean temperature causes ocean stratification, high surface water temperature, and hypoxia in the deep ocean (Keeling and Garcia 2002; Matear et al. 2000; Plattner and Verkhratsky 2016). At higher temperatures, O_2 consumption is increased by aquatic organisms, which further reduces the DO (Matear and Hirst 2003). This causes hypoxic water (Keeling and Garcia 2002; Matear et al. 2000; Plattner and Verkhratsky 2016). If the carbonic emission rate remains the same, the pH of the ocean water will be decreased by 0.4 pH units by 2100 (Meinshausen et al. 2011; Pörtner et al. 2014), average sea level will be raised by 0.67 m (Church et al. 2013) and the seawater surface temperature will rise by 2.73 °C and the oxygen content will decrease by 3.48% (Bopp et al. 2013). Global warming also changes the thermal and precipitation systems of freshwater ecosystems (Field et al. 2014; Füssel et al. 2012). Apart from this, acid rain lowers the pH value of freshwater bodies (acidification). This alternation in physical and chemical properties of aquatic ecosystems will certainly alter the physiology of fish. However, the effect of global warming on fisheries from the natural environment is very less (Pankhurst and King 2010; Strüssmann et al. 2010).

4 Environmental Stress and Fish Breeding

4.1 Stress and Reproduction

Primary stress hormones are due to the release of cortisol and catecholamines from the hypothalamic–pituitary–interrenal (adrenal) (HPI) axis and secondary stress response is caused by an increase in stress hormone level. Secondary stress responses take place at hematological, biochemical, immunological, osmoregulation, reproduction, and energy balance level (Schreck et al. 2001). Stressors also alter the behavior of the fish (Schreck et al. 1997), which may affect the reproductive process. Environmental stress triggers the level of cortisol in the blood plasma of fish very rapidly (Pankhurst 2011).

Cortisol decreases ovarian E2 production by downregulating the expression of cyp19a1a, thus decreasing vitellogenesis and influencing sex change (Carragher and Sumpter 1990; Milla et al. 2009). Stress mainly affects the HPI and HPG axis

(Mosconi et al. 2006). The fish HPI axis is described in detail by Norris and Hobbs (2006). He has discussed the role of cortisol on fish reproduction. Guerriero and Ciarcia (2006) reviewed stress and fish reproduction. The effect of stress depends on the time when it is experienced in the life cycle, severity, and duration. Stress encountered in one phase of development may give a response in the later phase. Pickering et al. (1987) reported that stress adversely affects fish reproduction. Brown trout, *Salmo trutta* exposed to crowding have increased plasma adrenocorticotropin hormone (ACTH), gonadotropin, cortisol, and reduced T and 11-KT. Subsequent studies have also revealed that stress gives a negative effect on fish reproduction (Campbell et al. 1992, 1994; Contreras-Sanchez et al. 1998; Schreck et al. 2001). Foo and Lam (1993) found that administration of exogenous hormone (cortisol) reduced the growth of oocytes, condition factor, serum testosterone, and E2 level in tilapia, *Oreochromis mossambicus*. The negative effect of cortisol is not mediated through inhibition of gonadotropin secretion in rainbow trout *Oncorhynchus mykiss* (Pankhurst and Van Der Kraak 2000). Contrary to this, Pankhurst et al. (1995) reported that the administration of cortisol does not change the level of testosterone and E2 in goldfish, *Carassius auratus*, carp, *Cyprinus carpio*, and a sparid, *Pagrus auratus*.

Secretion of ACTH is influenced by arginine and vasotocin (Balment et al. 2006). Urotensin-I regulates cortisol secretion in the Masu salmon, *Oncorhunchus masou* (Westring et al. 2008). Most of the fishes are gonochoristic and maintained the sex into which they are differentiated (Devlin and Nagahama 2002). The reproductive biology of these fishes is influenced by stress before sex differentiation but not after differentiation. Psycho-social stress regulates the sex change of protogynous wrasses (*Thalososoma sp.*). Bluehead wrasse, *T. bifasciatum* is a haremic species, in which the male is the head and the female has a social hierarchy. Taking out the male from the harem results in the conversion of dominant female to male (Robertson 1972). Protandrous hermaphrodites, clownfish, *Amphiprion nigripes*, is also a haremic-type fish, in which removal of dominant female leads to conversion of male to female (Godwin 1994). Population density and growth rate influence sex change in saddleback wrasse, *T. duperrey* (Ross 1987).

4.2 Effect of Temperature

Temperature is an important physical property of water, which influences the rate of biochemical reaction, structural changes at the molecular level, and physiological processes in vertebrates, including fish (Schulte et al. 2011). In teleost fish, thermoreceptors are present in the lateral line, connected to the central nervous system (Sullivan 1954). The majority of researchers agree with the distribution of thermoreceptor in the body (Fontaine 1976). Mechano-thermal of rainbow trout responds at more than 20 °C but not at a lower temperature (Ashley et al. 2007). Molecular sensors like TRPV1 and capsaicin for environmental heat are recognized in zebrafish (Gau et al. 2013) and other fishes (Gracheva and Bagriantsev 2015). Temperature important environmental factors regulate the fish reproductive cycle (Pankhurst and

King 2010; Strüssmann et al. 2010). High water temperatures affect the BPG axis and inhibit gonad development and reproduction in fishes (Tveiten and Johnsen 2001; King et al. 2003, 2007; Okuzawa et al. 2003; Pankhurst and King 2010; David and Degani 2011; Hermelink et al. 2011; Levy et al. 2011). Alternation in temperature inhibits fish reproduction by affecting the HPI axis (Pankhurst 2016). Temperature also damages the important sex organ, the gonad (Miranda et al. 2013). The higher temperature has irreparable effects on delicate life stages, viz. embryonic development, larvae, and sex determination/differentiation (Piferrer et al. 2005). Raised water temperature caused by global warming affects fish gonad development and maturation. Higher temperature disrupts the expression of the aromatase (*cyp19a1a*) gene in the gonad, which is responsible to convert testosterone to estrogen. This leads to disruption in estrogen production, downregulation of the aromatase gene, and disruption of oocyte growth (Anderson et al. 2012; Elisio et al. 2012; Lim et al. 2003; Watts et al. 2004). Disruption of estrogen synthesis inhibits vitellogenesis in the liver, thereby impacting oocyte growth/quality (Miranda et al. 2013). High water temperature alters the secretion of GnRH, gonadotrophin, and steroid hormone in salmonids (Van Der Kraak and Pankhurst 1997; Pankhurst and King 2010; Wang et al. 2010). Elevated temperature inhibits the synthesis and release of GnRH in red seabream (Okuzawa et al. 2003), blue gourami (Levy et al. 2011), and pejerrey (Elisio et al. 2012). Higher temperatures also inhibit the synthesis of pituitary gonadotrophin (FSH, LH) (Okuzawa et al. 2003; Soria et al. 2008; Gillet and Breton 2009; Levy et al. 2011; Elisio et al. 2012). Higher temperature inhibits steroidogenesis, which significantly reduces the plasma testosterone and 11-KT in male fish (Clark et al. 2005; Soria et al. 2008). Due to downregulation in the expression of the 11α-hydroxylase enzyme (convert T to 11-KT) at higher temperatures sperm count decreases in male fish (Lim et al. 2003; David and Degani 2011). Due to the thermal sensitivity of P450 aromatase, high temperature reduces E2 synthesis in female fish (Pankhurst and Munday 2011). High temperature during final maturation inhibits the synthesis of MIS, which leads to failure in final oocyte maturation in female fish (Gillet et al. 2011; Pankhurst and King 2010). At higher temperatures, lower P450 aromatase activity with simultaneous downregulation of *cyp19a* indicates that this lower activity is due to a problem in synthesis rather than post-translational modification of the enzyme (Elisio et al. 2012). In another study, higher temperature lowers the production of P450 aromatase and testosterone level which indicate that the higher temperature affects androgen synthesis in both male and female fish (Tveiten and Johnsen 2001; Elisio et al. 2012). Aromatase is a temperature-sensitive enzyme, which has a significant role in sex differentiation and determination in fish (Guiguen et al. 2010). Furthermore, the higher temperature at critical time windows of early development can modify gonadal sex (Strüssmann et al. 1997). Increased water temperature affects sex determination through the HPI axis (Pankhurst 2016). Increased temperature prompts methylation of *cyp19a1a* gene promoter that inhibits aromatase expression and masculinization of genotypic females (Navarro-Martín et al. 2011). High temperature also has masculinization effect on seabass (Piferrer et al. 2005; Paullada-Salmerón et al. 2017). Juvenile sole exposed to natural daily thermo-cycle decreases 11-KT, T level and increases female to male sex ratio compared to constant temperature (Blanco-Vives et al. 2011). Larvae (Pejerrey, medaka, and Japanese flounder) reared at high temperature changed to male and have high body cortisol levels. This change is inhibited by treatment with cortisol inhibitors (Hattori et al. 2009; Hayashi et al. 2010; Yamaguchi et al. 2010). Fish eggs and larvae are very sensitive and have less tolerance to thermal stress (Rombough 1997). Larvae growth increases with an increase in temperature in both temperate and tropical areas (Green and Fisher 2004). Gametogenesis in fish is controlled by temperature and other environmental cues (Zanuy et al. 1986; Migaud et al. 2002, Lahnsteiner and Kletzl 2012). Oocyte size/morphology (Mansour et al. 2007), ovarian fluid quality/pH (Aegerter and Jalabert 2004), sperm motility (Muller et al. 2008; Zilli et al. 2004), rate of fertilization and fertilized eggs buoyancy (Shields et al. 1997), embryonic development, survival, deformities, hatching, and yolk sac utilization (Bobe and Labbe 2010; Bonnet et al. 2007) depend on several endogenous and exogenous factors. Temperature change shift spawning period (Bobe and Labbe 2010; Miranda et al. 2013), reduced fecundity (Pankhurst et al. 1996; Pankhurst and Thomas 1998), fertility (Miranda et al. 2013, Hutchings and Myers 1994; Lahnsteiner and Kletzl 2012; King et al. 2003, 2007), Atlantic salmon (King et al. 2003, 2007; Aegerter and Jalabert 2004), embryo survival (Pankhurst et al. 1996; Pankhurst and Thomas 1998; Tveiten et al. 2001), and deformity (Aegerter and Jalabert 2004). An increase in temperature before spawning (pre-spawning period) leads to delay and advance the spawning of fall spawner and spring spawner, respectively. This is due to the decrease and increase in E2 levels in the fall and spring spawner, respectively. In fall spawners, the higher temperature during the spawning phase disrupts the MIS synthesis (Gillet et al. 2011; King et al. 2003, 2007; Pankhurst et al. 1996; Pankhurst and Thomas 1998). In spring spawners, the higher temperature during the spawning phase decreased the E2 level (Hutchings and Myers 1994; Miranda et al. 2013; Newman et al. 2010; Tveiten 2008). It is observed that high temperature delays spawning in fall spawner fish (autumn spawner) and gives a signal of spawning in spring spawner (Miranda et al. 2013). Higher temperature also affects phospholipids, triacylglycerols, and the free fatty acid content of oocytes (Jobling et al. 1995; Lahnsteiner and Leitner 2013). The larvae produced from parents, which area reared at higher temperatures showed more thermal tolerance (Rombough 1997).

4.3 Effect of Salinity

Water salinity influences osmoregulation and breeding of fish. These biological processes require energy, thus the fish has to make adjustments to maintain homeostasis balance with its surrounding environmental medium and to decrease osmoregulatory expenditure (Sampaio and Bianchini 2002). Inappropriate external salinity levels can cause fish mortality and stress and long-term stress can impair the growth of fish and immune system as well as affect its reproductive development (Campbell et al. 1994; Castranova et al. 2005; Davis et al. 2002). Salinity altered the reproductive performance (Haddy and Pankhurst 1998, 2000) and sex ratio (Saillant et al.

2003). Temperature and salinity influence testis maturation and sex change in seabass (Athauda and Anderson 2012). Seabass (*Lates calcarifer*) reared in freshwater recirculatory aquaculture system developed testis after 9 months of rearing. Opposite to this, European, seabass (*Dicentrarchus labrax*) reared at 3.5 ppt and 37.8 ppt of salinities did not show the difference in gonadal recrudescence (Zanuy and Carrillo 1985). Tested salinity from 5 to 33 ppt did not affect the reproductive performance of the female scat fish, a higher ovulation rate was obtained within the middle range of salinities (15 and 25 ppt) (Ruensirikul and Chiayvareesajja 2020). Salinity affects directly the rate of fertilization, survival percentage, and development of fish (Holliday 1969). European seabass *Dicentrarchus labrax* (Zanuy and Carrillo 1985); striped mullet *M. cephalus* (Lee and Weber 1986; Tamaru et al. 1994), and black bream *Acanthopagrus butcheri* (Haddy and Pankhurst 2000) oocyte development does not get affected by salinity. However, the number of ovulations and egg volume in these species is low when reared at 5 ppt of salinity. Recently, Kumar et al. 2020 observed the maturation *L. parsia* at 5–8 ppt (mean: 7 ± 1.5 ppt) of salinity. Maturation of *L. parsia* at 7 ppt was also reported by Alam et al. (2008). Salinity also alters the activity of the aromatase enzyme (Athauda and Anderson 2014). The HPG axis is the main axis that regulates the sex change in fish. Apart from this HPI axis also regulates sex change (Perry and Grober 2003; Gardner et al. 2005, Solomon-Lane et al. 2013).

In marine fish, salinity influences fertilization, development, hatching, and survival (Nissling and Larsson 2018; Nissling et al. 2006, 2017; Westin and Nissling 1991). Change in hormone profiles of male and female guppies at different salinities is reported by Moniruzzaman et al. 2018. Low salinity affects spermatozoa speed and motility in European flounder (Nissling and Larsson 2018). Water salinity, osmolarity, and pH regulate sperm motility (Alavi and Cosson 2006; Magnotti et al. 2018, Billard 1978; Billard et al. 1993; Effer et al. 2013; Yeganeh et al. 2008). In testis and seminal plasma (isotonic), spermatozoa remain in a non-active state. Once spermatozoa are out into the fresh (hypoosmotic) or marine water (hyperosmotic) the motility is activated in freshwater or marine species, respectively (Alavi and Cosson 2006; Billard 1986; Morisawa and Suzuki 1980; Stoss 1983). In marine fish, saline water causes exosmosis in the spermatozoa and increases the concentration of Ca^{+2} ions, which activate the motility (Boj et al. 2015; Cosson et al. 2008). The unsuitable salt concentration, osmolality, and pH of water depolarize the cell membrane of spermatozoa, which disturbs the spermatozoa motility (Morisawa and Suzuki 1980; Morisawa et al. 1983). The decreased sperm motility reduces the fertilization rate (Cosson 2004; Cosson et al. 1985; Stoss 1983).

4.4 Effect of Hypoxia

Hypoxia condition is found once the dissolved oxygen level is below 2.8 mg O_2/L (equivalent to 2 mL O_2/L) (Diaz and Rosenberg 1995). Hypoxia acts as an endocrine disruptor by regulating steroidogenesis and it has a teratogen effect on the embryonic development of several fish. Hypoxia influences the BPG axis at various points and influences the reproductive function of fish (Wu 2009). Hypoxia (0.6 mg O_2/L) induced for 3 weeks in zebrafish downregulates the expression of FSHβ mRNA. In the same species, chronic hypoxia (1.8 mg O_2/L) for 3 months suppresses the expression of ovary FSH receptor and tryptophan hydroxylase mRNA (Wu 2009). Hypoxic condition downregulates the expression of GnRH in the brain and gonadotropin in the pituitary of zebrafish (Lu et al. 2014), and in Atlantic croaker, hypoxia inhibits brain GnRH expression and decreases serotonin levels (Thomas et al. 2007). Oxygen is essentially required for steroidogenesis; therefore, the hypoxic condition significantly downregulates the sex steroid hormones (E2, T, 11-KT) in Atlantic croaker (*Micropogonias undulatus*) (Raff and Bruder 2006). Hypoxia reduces E2 and 11-KT levels in both sexes of Gulf killifish (*Fundulus grandis*) without altering the T and vitellogenin (Landry et al. 2007). The hypoxic condition reduces vitellogenin, hepatic estrogen receptor, and gonadosomatic index (GSI) in fish (Thomas et al. 2006; Wu et al. 2003). Hypoxia also has a significant effect on the embryonic and larval development of fish (Wu et al. 2003). Hypoxia reduces survival, and growth during hatching slows embryonic growth and increases embryonic deformities in fish (Shang and Wu 2004; Marks et al. 2012; Del Rio et al. 2019; Saha et al. 2022). Hypoxia also altered the reproductive behavior of marine gobies (Jones and Reynolds 1999). In general, blastula and gastrula are most vulnerable to stress (Cameron and Hein Von 1997). Hypoxia reduces the ontogenesis of brown trout alevin (Dumas et al. 2007). Hatching is an energy-demanding process due to more oxygen uses and movement by the embryo (Hamor and Garside 1976). During hypoxic conditions incubation time may increase due to delay in development or decrease due to an increase in metabolic rate (Rombough 1988). Low oxygen (hypoxia) is a natural signal for the hatching of an embryo in a few fishes (Czerkies et al. 2001). The hypoxic condition reduces the viability of sperm and eggs in both laboratory and field conditions of fish (Thomas et al. 2007, 2015; Thomas and Rahman 2012; Cheek et al. 2009; Landry et al. 2007; Wu et al. 2003; Wang et al. 2016). Ovarian masculinization is found in 19% of female Atlantic croakers in a hypoxic zone (Thomas and Rahman 2012). Hypoxia induces masculinization and altered sex ratio in zebrafish (Shang and Wu 2004). This might be due to a decrease in ovarian aromatase activity (Shang and Wu 2004; Thomas and Rahman 2012; Thomas et al. 2015). Recently, Bera et al. 2017 reported the impact of hypoxia on lipid dynamics in goldfish. They reported the depletion of total cholesterol and high-density lipoprotein (HDL) and an increase in triglycerides (TG) in goldfish. This depletion reduces the availability of cholesterol. A decrease in cholesterol levels alters the sex steroid profiles (Scott 1987; Bera et al. 2017). Hypoxia decreases the expression of membrane progestin receptor alpha (mPRα) in gametes, which disrupts the final oocyte and sperm maturation (Thomas et al. 2015).

4.5 Effect of Acidification

Published literature is scarce on the effect of low pH (water acidification) and elevated pCO_2 on the reproductive biology of fish. An increase in reproductive performance was noted in an acidic condition in some fishes (Schade et al. 2014) and coral fish *A*. melanopus (Miller et al. 2013). Similarly, a positive correlation between PCO_2 on breeding is reported by Miller et al. (2015). The acidic condition does not affect the functional fecundity of *Ocellated wrasse* (Milazzo et al. 2016) and two-spotted goby (Forsgren et al. 2013). In another report, in two-spotted goby stimulatory effect on breeding performance is reported by Faria et al. (2018). Kikkawa et al. (2004) reported the relatively poor survival of red seabream (*Pagrus major*) larvae exposed to lower pH due to carbon dioxide than mineral acid HCl. This might be due to more permeability of biomembrane to CO_2 than H^+ (Morris et al. 1989). Higher concentrations of CO_2 damage the olfactory system of clownfish and damselfish larvae (Munday et al. 2009, 2010). There are two hypotheses by which acidic conditions affect the reproduction of fish. The first one is the GABA model hypothesis, where high PCO_2 disrupted the GABA receptor, which affects the release of GnRH from the brain and gonadotropin from the pituitary gland of fish (Nilsson et al. 2012). The GABA may inhibit or stimulate gametogenesis (Trudeau et al. 1993), which depends on the species. Another hypothesis is an effect due to change in circadian rhythms systems in fish as per PCO_2 concentration (Servili et al. 2010, 2020; Schunter et al. 2016).

4.6 Effect of Photoperiod

Fishes of temperate and cold regions are seasonal breeders and the reproductive cycle is controlled by temperature and/or photoperiod (day length). Temperature and photoperiod regulate the spawning time for maximum survival of spawn (Bromage et al. 2001; Pörtner and Farrell 2008). Temperature and rainfall control the reproductive cycle in tropical and subtropical regions.

Changing temperature may alter the timing and season of reproduction in fish (Durant et al. 2007). Manipulation of photoperiod influences fish physiology such as growth, reproduction, and gonadal maturation (Boeuf and Le Bail 1999; Bromage et al. 2001; Biswas et al. 2005). Extended photoperiod enhances growth and slows the sexual maturity in Atlantic salmon (*Salmo salar*), Rainbow trout (*Oncorhynchus mykiss*), Atlantic halibut (*Hippoglossus hippoglossus*), seabream (*Sparus aurata*), and European seabass (*D. labrax*) (Boeuf and Le Bail 1999; Oppedal et al. 1999; Simensen et al. 2000; Rodrı́guez et al. 2001; Gines et al. 2004).

4.7 Effect of Lunar Cycle

The lunar cycle influences the fish (especially reef fish) physiology and synchronizes many physiological events like gonad development and spawning (Takemura et al. 2004). The lunar cycle offers reliable time cues for reproductive synchrony (Skov et al. 2005). The onset of migration and spawning of fish depends on tidal height (Karppinen et al. 2004) and the period of the lunar cycle (Kuparinen et al. 2009). Marine fish shows periodicity with lunar and semi-lunar phase for breeding (Greeley et al. 1986; Rahman et al. 2003; Takemura et al. 2004), with maximum spawning around the new or full moon (Johannes 1978). A sudden increase in 11-KT and T is noticed around the new moon in male rabbit fish (Hoque et al. 1999; Rahman et al. 2003; Takemura et al. 2004).

5 Conclusion

Global climate change and its effect on aquatic animals especially vertebrates is the burning current research issue. Therefore, understanding the effect of different environmental and changing physico-chemical parameters on the reproductive cycle and endocrinology of fish will help to develop strategies for mitigation measures and conservation. The current review is focused on the effect of temperature, hypoxia, salinity, pH, lunar cycle, and photoperiod on fish endocrinology and breeding.

References

Aegerter S, Jalabert B (2004) Effects of post-ovulatory oocyte aging and temperature on egg quality and on the occurrence of triploid fry in rainbow trout, *Oncorhynchus mykiss*. Aquaculture 231(1–4):59–71

Alam SM, Watanabe WO, Carroll PM (2008) Dietary protein requirements of juvenile black sea bass, Centropristis striata. J World Aquacult Soc 39(5):656–663

Alavi SMH, Cosson J (2006) Sperm motility in fishes. (II) effects of ions and osmolality: a review. Cell Biol Int 30(1):1–14

Anderson K, Swanson P, Pankhurst N et al (2012) Effect of thermal challenge on plasma gonadotropin levels and ovarian steroidogenesis in female maiden and repeat spawning Tasmanian Atlantic salmon (*Salmo salar*). Aquaculture 334:205–212

Ashley PJ, Sneddon LU, McCrohan CR (2007) Nociception in fish: stimulus-response properties of receptors on the head of trout *Oncorhynchus mykiss*. Brain Res 1166:47–54

Athauda S, Anderson T (2014) Effect of temperature and salinity on sex inversion in Asian seabass (*Lates calcarifer*): relationship with plasma sex steroids concentration and aromatase activity of gonad and brain. Aquacult Res 45(5):787–797

Athauda S, Anderson T, De-Nys R (2012) Effect of rearing water temperature on protandrous sex inversion in cultured Asian seabass (*Lates calcarifer*). Gen Comp Endocrinol 175(3):416–423

Balment RJ, Lu W, Weybourne E et al (2006) Arginine vasotocin a key hormone in fish physiology and behavior: a review with insights from mammalian models. Gen Comp Endocrinol 147(1): 9–16

Bera A, Sawant PB, Dasgupta S et al (2017) Diel cyclic hypoxia alters plasma lipid dynamics and impairs reproduction in goldfish (*Carassius auratus*). Fish Physiol Biochem 43(6):1677–1688

Billard R (1978) Changes in structure and fertilizing ability of marine and freshwater fish spermatozoa diluted in media of various salinities. Aquaculture 14(3):187–198

Billard R (1986) Spermatogenesis and spermatology of some teleost fish species. Reprod Nutr Dev 26(4):877–920

Billard R, Cosson J, Crim LW (1993) Motility of fresh and aged halibut sperm. Aquat Living Resour 6(1):67–75

Blanco-Vives B, Vera LM, Ramos J et al (2011) Exposure of larvae to daily thermocycles affects gonad development, sex ratio, and sexual steroids in *Solea senegalensis*, kaup. J Exp Zool A Ecol Genet Physiol 315(3):162–169

Bobe J, Labbé C (2010) Egg and sperm quality in fish. Gen Comp Endocrinol 165(3):535–548

Boeuf G, Le Bail PY (1999) Does light have an influence on fish growth? Aquaculture 177(1–4): 129–152

Boj M, Chauvigne F, Cerda J (2015) Aquaporin biology of spermatogenesis and sperm physiology in mammals and teleosts. Biol Bull 229(1):93–108

Bonnet E, Montfort J, Esquerre D et al (2007) Effect of photoperiod manipulation on rainbow trout (*Oncorhynchus mykiss*) egg quality: a genomic study. Aquaculture 268(1–4):13–22

Bopp L, Resplandy L, Orr JC et al (2013) Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. Biogeosciences 10(10):6225–6245

Brander KM (2010) Cod *Gadus morhua* and climate change: processes, productivity and prediction. J Fish Biol 77(8):1899–1911

Bromage N, Porter M, Randall C (2001) The environmental regulation of maturation in farmed finfish with special reference to the role of photoperiod and melatonin. Aquaculture 197(1): 63–98

Cameron P, Hein Von W (1997) Malformation rates in embryos of North Sea fishes in 1991 and 1992. Mar Pollut Bull 34(2):129–134

Campbell PM, Pottinger TG, Sumpter JP (1992) Stress reduces the quality of gametes produced by rainbow trout. Biol Reprod 47(6):1140–1150

Campbell PM, Pottinger TG, Sumpter JP (1994) Preliminary evidence that chronic confinement stress reduces the quality of gametes produced by brown and rainbow trout. Aquaculture 120(1–2):151–169

Carragher JF, Sumpter JP (1990) The effect of cortisol on the secretion of sex steroids from cultured ovarian follicles of rainbow trout. Gen Comp Endocrinol 77(3):403–407

Castranova DA, King W, Woods LC III (2005) The effects of stress on androgen production, spermiation response and sperm quality in high and low cortisol responsive domesticated male striped bass. Aquaculture 246(1–4):413–422

Cheek AO, Landry CA, Steele SL et al (2009) Diel hypoxia in marsh creeks impairs the reproductive capacity of estuarine fish populations. Mar Ecol Prog Ser 392:211–221

Church JA, Clark PU, Cazenave A et al (2013) Sea level change. Cambridge University Press, Cambridge

Clark RW, Henderson-Arzapalo A, Sullivan CV (2005) Disparate effects of constant and annually-cycling daylength and water temperature on reproductive maturation of striped bass (Morone saxatilis). Aquaculture 249(1–4):497–513

Contreras-Sanchez WM, Schreck CB, Fitzpatrick MS et al (1998) Effects of stress on the reproductive performance of rainbow trout (*Oncorhynchus mykiss*). Biol Reprod 58(2):439–447

Cosson J (2004) The ionic and osmotic factors controlling motility of fish spermatozoa. Aquac Int 12(1):69–85

Cosson MP, Billard R, Gatti JL et al (1985) Rapid and quantitative assessment of trout spermatozoa motility using stroboscopy. Aquaculture 46(1):71–75

Cosson J, Groison AL, Suquet M et al (2008) Marine fish spermatozoa: racing ephemeral swimmers. Reproduction 136(3):277–294

Czerkies P, Brzuzan P, Kordalski K et al (2001) Critical partial pressures of oxygen causing precocious hatching in *Coregonus lavaretus* and *C. albula* embryos. Aquaculture 196(1–2): 151–158

David D, Degani G (2011) Temperature affects brain and pituitary gene expression related to reproduction and growth in the male blue gouramis, *Trichogaster trichopterus*. J Exp Zool A Ecol Genet Physiol 315(4):203–214

Davis KB, Griffin BR, Gray WL (2002) Effect of handling stress on susceptibility of channel catfish *Ictalurus punctatus* to *Ichthyophthirius multifiliis* and channel catfish virus infection. Aquaculture 214(1–4):55–66

Del Rio AM, Davis BE, Fangue NA et al (2019) Combined effects of warming and hypoxia on early life stage chinook salmon physiology and development. Conserv Physiol 7(1):coy078

Devlin RH, Nagahama Y (2002) Sex determination and sex differentiation in fish: an overview of genetic, physiological, and environmental influences. Aquaculture 208(3–4):191–364

Diaz RJ, Rosenberg R (1995) Marine benthic hypoxia: a review of its ecological effects and the behavioural responses of benthic macrofauna. Oceanogr Mar Biol 33:245–303

Dumas J, Bassenave JG, Jarry M et al (2007) Effects of fish farm effluents on egg-to-fry development and survival of brown trout in artificial redds. J Fish Biol 70(6):1734–1758

Durant JM, Hjermann DØ, Ottersen G et al (2007) Climate and the match or mismatch between predator requirements and resource availability. Climate Res 33(3):271–283

Effer B, Figueroa E, Augsburger A et al (2013) Sperm biology of *Merluccius australis*: sperm structure, semen characteristics and effects of pH, temperature and osmolality on sperm motility. Aquaculture 408:147–151

Elisio M, Chalde T, Miranda LA (2012) Effects of short periods of warm water fluctuations on reproductive endocrine axis of the pejerrey (*Odontesthes bonariensis*) spawning. Comp Biochem Physiol A Mol Integr Physiol 163(1):47–55

Faria AM, Lopes AF, Silva CD et al (2018) Reproductive trade-offs in a temperate reef fish under high pCO2 levels. Mar Environ Res 137:8–15

Ficke AD, Myrick CA, Hansen LJ (2007) Potential impacts of global climate change on freshwater fisheries. Rev Fish Biol Fish 17(4):581–613

Field CB, Barros VR, (Eds.). (2014) Climate change 2014–impacts, adaptation and vulnerability: regional aspects. Cambridge University Press, Cambridge

Fontaine M (1976) Physiological mechanisms in the migration of marine and amphihaline fish. In: Advances in marine biology, vol 13. Academic Press, Cambridge, pp 241–355

Foo JTW, Lam TJ (1993) Serum cortisol response to handling stress and the effect of cortisol implantation on testosterone level in the tilapia, *Oreochromis mossambicus*. Aquaculture 115(1–2):145–158

Forsgren E, Dupont S, Jutfelt F et al (2013) Elevated CO2 affects embryonic development and larval phototaxis in a temperate marine fish. Ecol Evol 3(11):3637–3646

Füssel J, Lam P, Lavik G et al (2012) Nitrite oxidation in the Namibian oxygen minimum zone. ISME J 6(6):1200–1209

Gardner L, Anderson T, Place AR et al (2005) Sex change strategy and the aromatase genes. J Steroid Biochem Mol Biol 94(5):395–404

Gattuso JP, Magnan A, Billé R et al (2015) Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. Science 349(6243):aac4722

Gau P, Poon J, Ufret-Vincenty C et al (2013) The zebrafish ortholog of TRPV1 is required for heat-induced locomotion. J Neurosci 33(12):5249–5260

Gillet C, Breton B (2009) LH secretion and ovulation following exposure of Arctic charr to different temperature and photoperiod regimes: responsiveness of females to a gonadotropin-releasing hormone analogue and a DA. Gen Comp Endocrinol 162(2):210–218

Gillet C, Breton B, Mikolajczyk T et al (2011) Disruption of the secretion and action of 17, 20-β-dihydroxy-4-pregnen-3-one in response to a rise in temperature in the Arctic charr, *Salvelinus alpinus*. Consequences on oocyte maturation and ovulation. Gen Comp Endocrinol 172(3): 392–399

Ginés R, Afonso JM, Argüello A et al (2004) The effects of long-day photoperiod on growth, body composition and skin colour in immature gilthead sea bream (*Sparus aurata* L.). Aquacult Res 35(13):1207–1212

Godwin J (1994) Historical aspects of protandrous sex change in the anemonefish *Amphiprion melanopus* (Pomacentridae, teleostei). J Zool 232(2):199–213

Gracheva EO, Bagriantsev SN (2015) Evolutionary adaptation to thermo-sensation. Curr Opin Neurobiol 34:67–73

Greeley MS, Marion KR, MacGregor R (1986) Semilunar spawning cycles of *Fundulus similis* (Cyprinodontidae). Environ Biol Fishes 17(2):125–131

Green BS, Fisher R (2004) Temperature influences swimming speed, growth and larval duration in coral reef fish larvae. J Exp Mar Biol Ecol 299(1):115–132

Guerriero G, Ciarcia G (2006) Stress biomarkers and reproduction in fish. Fish Endocrinol 2(514): 665–692

Guiguen Y, Fostier A, Piferrer F, Chang CF (2010) Ovarian aromatase and estrogens: a pivotal role for gonadal sex differentiation and sex change in fish. Gen Comp Endocrinol 165(3):352–366

Haddy JA, Pankhurst NW (1998) Annual change in reproductive condition and plasma concentrations of sex steroids in black bream, *Acanthopagrus butcheri* (Munro) (Sparidae). Mar Freshw Res 49(5):389–397

Haddy JA, Pankhurst NW (2000) The effects of salinity on reproductive development, plasma steroid levels, fertilisation and egg survival in black bream *Acanthopagrus butcheri*. Aquaculture 188(1–2):115–131

Hamor T, Garside ET (1976) Developmental rates of embryos of Atlantic salmon, *Salmo salar* L., in response to various levels of temperature, dissolved oxygen, and water exchange. Can J Zool 54(11):1912–1917

Hattori RS, Fernandino JI, Kishii AI et al (2009) Cortisol-induced masculinization: does thermal stress affect gonadal fate in pejerrey, a teleost fish with temperature-dependent sex determination? PLoS One 4(8):e6548

Hayashi Y, Kobira H, Yamaguchi T et al (2010) High temperature causes masculinization of genetically female medaka by elevation of cortisol. Mol Reprod Dev 77(8):679–686

Hermelink B, Wuertz S, Trubiroha A et al (2011) Influence of temperature on puberty and maturation of pikeperch, *Sander lucioperca*. Gen Comp Endocrinol 172(2):282–292

Holliday FGT (1969) The effects of salinity on the eggs and larvae of Teleosts. Fish Physiol 1:293–311

Hoque MM, Takemura A, Matsuyama M et al (1999) Lunar spawning in *Siganus canaliculatus*. J Fish Biol 55(6):1213–1222

Hutchings JA, Myers RA (1994) Timing of cod reproduction: interannual variability and the influence of temperature. Mar Ecol Prog Ser 108(1):21–32

Jalabert B (2005) Particularities of reproduction and oogenesis in teleost fish compared to mammals. Reprod Nutr Dev 45(3):261–279

Jobling M, Arnesen AM, Baardvik BM, Christiansen JS, Jørgensen EH (1995) Monitoring feeding behaviour and food intake: methods and applications. Aquacult Nutr 1(3):131–143

Johannes RE (1978) Reproductive strategies of coastal marine fishes in the tropics. Environ Biol Fishes 3(1):65–84

Jones JC, Reynolds JD (1999) Costs of egg ventilation for male common gobies breeding in conditions of low dissolved oxygen. Anim Behav 57(1):181–188

Karppinen P, Erkinaro J, Niemelä et al (2004) Return migration of one-sea-winter Atlantic salmon in the river tana. J Fish Biol 64(5):1179–1192

Keeling RF, Garcia HE (2002) The change in oceanic O2 inventory associated with recent global warming. Proc Natl Acad Sci 99(12):7848–7853

Kikkawa T, Kita J, Ishimatsu A (2004) Comparison of the lethal effect of CO2 and acidification on red sea bream (Pagrus major) during the early developmental stages. Mar Pollut Bull 48(1–2): 108–110

King HR, Pankhurst NW, Watts M et al (2003) Effect of elevated summer temperatures on gonadal steroid production, vitellogenesis and egg quality in female Atlantic salmon. J Fish Biol 63(1): 153–167

King HR, Pankhurst NW, Watts M (2007) Reproductive sensitivity to elevated water temperatures in female Atlantic salmon is heightened at certain stages of vitellogenesis. J Fish Biol 70(1): 190–205

Kumar P, Biswas G, Ghoshal TK et al (2020) Effect of salinity acclimatisation and administration of hormones on oocyte maturation, ovulation and spawning of goldspot mullet Liza parsia (Hamilton, 1822) reared in brackishwater pond. Indian J Fish 67(1):56–63

Kumar P, Behera P, Biswas G et al (2022) Oocyte growth, gonadosomatic index, hepatosomatic index and levels of reproductive hormones in goldspot mullet Planiliza parsia (Hamilton, 1822) reared in captivity. Indian J Fish 69(1):84–96

Kuparinen A, Kuikka S, Merilä J (2009) Estimating fisheries-induced selection: traditional gear selectivity research meets fisheries-induced evolution. Evol Appl 2(2):234–243

Lahnsteiner F, Kletzl M (2012) The effect of water temperature on gamete maturation and gamete quality in the European grayling (*Thymallus thymallus*) based on experimental data and on data from wild populations. Fish Physiol Biochem 38(2):455–467

Lahnsteiner F, Leitner S (2013) Effect of temperature on gametogenesis and gamete quality in brown trout, Salmo trutta. J Exp Zool A Ecol Genet Physiol 319(3):138–148

Landry CA, Steele SL, Manning S et al (2007) Long term hypoxia suppresses reproductive capacity in the estuarine fish, Fundulus grandis. Comp Biochem Physiol A Mol Integr Physiol 148(2): 317–323

Lee CS, Weber GM (1986) Effects of salinity and photoperiod on 17α-methyltestosterone-induced spermatogenesis in the grey mullet, *Mugil cephalus* L. Aquaculture 56(1):53–62

Levy G, David D, Degani G (2011) Effect of environmental temperature on growth-and reproduction-related hormones gene expression in the female blue gourami (*Trichogaster trichopterus*). Comp Biochem Physiol A Mol Integr Physiol 160(3):381–389

Lim BS, Kagawa H, Gen K et al (2003) Effects of water temperature on the gonadal development and expression of steroidogenic enzymes in the gonad of juvenile red seabream, *Pagrus major*. Fish Physiol Biochem 28(1):161–162

Lu X, Richard MK, Murphy MB et al (2014) Hypoxia disrupts gene modulation along the brain–pituitary–gonad (BPG)–liver axis. Ecotoxicol Environ Saf 102:70–78

Magnotti C, Figueroa E, Farias JG et al (2018) Sperm characteristics of wild and captive lebranche mullet Mugil liza (Valenciennes, 1836), subjected to sperm activation in different pH and salinity conditions. Anim Reprod Sci 192:164–170

Mansour N, Lahnsteiner F, Patzner RA (2007) Distribution of lipid droplets is an indicator for egg quality in brown trout, *Salmo trutta fario*. Aquaculture 273(4):744–747

Marks C, Kaut KP, Moore FG et al (2012) Ontogenetic oxygen changes alter zebra fish size, behavior, and blood glucose. Physiol Biochem Zool 85(6):635–644

Matear RJ, Hirst AC (2003) Long-term changes in dissolved oxygen concentrations in the ocean caused by protracted global warming. Global Biogeochem Cycles 17(4):1125

Matear RJ, Hirst AC, McNeil BI (2000) Changes in dissolved oxygen in the Southern Ocean with climate change. Geochem Geophys Geosyst 1(11):2000GC000086

Meinshausen M, Raper SC, Wigley TM (2011) Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6–part 1: model description and calibration. Atmos Chem Phys 11(4):1417–1456

Migaud H, Fontaine P, Sulistyo I et al (2002) Induction of out-of-season spawning in Eurasian perch *Perca fluviatilis*: effects of rates of cooling and cooling durations on female gametogenesis and spawning. Aquaculture 205(3–4):253–267

Milazzo M, Cattano C, Alonzo SH et al (2016) Ocean acidification affects fish spawning but not paternity at CO2 seeps. Proc R Soc B Biol Sci 283(1835):20161021

Milla S, Wang N, Mandiki SNM et al (2009) Corticosteroids: friends or foes of teleost fish reproduction? Comp Biochem Physiol A Mol Integr Physiol 153(3):242–251

Miller GM, Watson SA, McCormick MI et al (2013) Increased CO2 stimulates reproduction in a coral reef fish. Glob Chang Biol 19(10):3037–3045

Miller GM, Kroon FJ, Metcalfe S et al (2015) Temperature is the evil twin: effects of increased temperature and ocean acidification on reproduction in a reef fish. Ecol Appl 25(3):603–620

Miranda LA, Chalde T, Elisio M et al (2013) Effects of global warming on fish reproductive endocrine axis, with special emphasis in pejerrey *Odontesthes bonariensis*. Gen Comp Endocrinol 192:45–54

Moniruzzaman M, Mukherjee J, Jacquin L et al (2018) Physiological and behavioural responses to acid and osmotic stress and effects of Mucuna extract in guppies. Ecotoxicol Environ Saf 163: 37–46

Montserrat N, González A, Méndez E et al (2004) Effects of follicle stimulating hormone on estradiol-17β production and P-450 aromatase (CYP19) activity and mRNA expression in brown trout vitellogenic ovarian follicles in vitro. Gen Comp Endocrinol 137(2):123–131

Morisawa M, Suzuki K (1980) Osmolality and potassium ion: their roles in initiation of sperm motility in teleosts. Science 210(4474):1145–1147

Morisawa M, Suzuki K, Morisawa S (1983) Effects of potassium and osmolality on spermatozoan motility of salmonid fishes. J Exp Biol 107(1):105–113

Morris RJ, Law RJ, Allchin CR et al (1989) Metals and organochlorines in dolphins and porpoises of Cardigan Bay, West Wales Marine. Pollut Bull 20(10):512–523

Mosconi G, Yamamoto K, Kikuyama S et al (2006) Neuroendocrine modulation of stress response in the anuran, Rana esculenta. Amphibia-Reptilia 27(3):401–408

Muller UK, Van den Boogaart JG, Van Leeuwen JL (2008) Flow patterns of larval fish: undulatory swimming in the intermediate flow regime. J Exp Biol 211(2):196–205

Munday PL, Dixson DL, Donelson JM, Jon et al (2009) Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. Proc Natl Acad Sci 106(6):1848–1852

Munday PL, Dixson DL, McCormick MI et al (2010) Replenishment of fish populations is threatened by ocean acidification. Proc Natl Acad Sci 107(29):12930–12934

Nagahama Y, Yamashita M (2008) Regulation of oocyte maturation in fish. Dev Growth Differ 50: S195–S219

Nagahama Y, Yoshikuni M, Yamashita M et al (1994) Regulation of oocyte maturation in fish. In: Fish physiology, vol 13. Academic Press, Cambridge, pp 393–439

Navarro-Martín L, Viñas J, Ribas L et al (2011) DNA methylation of the gonadal aromatase (*cyp19a*) promoter is involved in temperature-dependent sex ratio shifts in the European sea bass. PLoS Genet 7(12):e1002447

Nelson LE, Sheridan MA (2006) Gastroenteropancreatic hormones and metabolism in fish. Gen Comp Endocrinol 148(2):116–124

Newman DM, Jones PL, Ingram BA (2010) Advanced ovarian development of Murray cod Maccullochella peelii peelii via phase-shifted photoperiod and two temperature regimes. Aquaculture 310(1–2):206–212

Nilsson GE, Dixson DL, Domenici P et al (2012) Near-future carbon dioxide levels alter fish behaviour by interfering with neurotransmitter function. Nat Clim Chang 2(3):201–204

Nissling A, Larsson R (2018) Population specific sperm production in European flounder Platichthys flesus: adaptation to salinity at spawning. J Fish Biol 93(1):47–52

Nissling A, Johansson U, Jacobsson M (2006) Effects of salinity and temperature conditions on the reproductive success of turbot (Scophthalmus maximus) in the Baltic Sea. Fish Res 80(2–3): 230–238

Nissling A, Nyberg S, Petereit C (2017) Egg buoyancy of flounder, *Platichthys flesus*, in the Baltic Sea—adaptation to salinity and implications for egg survival. Fish Res 191:179–189

Norris DO, Hobbs SL (2006) The HPA axis and functions of corticosteroids in fishes. In: Reinecke M, Zaccone G, Kapoor BG (eds) Fish endocrinology, vol 2, pp 721–765

Okuzawa K, Kumakura N, Gen K et al (2003) Effect of high water temperature on brain-pituitary-gonad axis of the red seabream during its spawning season. Fish Physiol Biochem 28(1): 439–440

Oppedal F, Taranger GL, Juell JE (1999) Growth, osmoregulation and sexual maturation of underyearling Atlantic salmon smolt *Salmo salar* L. exposed to different intensities of continuous light in sea cages. Aquacult Res 30(7):491–499

Pankhurst NW (2011) The endocrinology of stress in fish: an environmental perspective. Gen Comp Endocrinol 170(2):265–275

Pankhurst NW (2016) Reproduction and development. In: Fish physiology, vol 35. Academic Press, Cambridge, US, pp 295–331

Pankhurst NW, King HR (2010) Temperature and salmonid reproduction: implications for aquaculture. J Fish Biol 76(1):69–85

Pankhurst NW, Munday PL (2011) Effects of climate change on fish reproduction and early life history stages. Mar Freshw Res 62(9):1015–1026

Pankhurst NW, Thomas PM (1998) Maintenance at elevated temperature delays the steroidogenic and ovulatory responsiveness of rainbow trout *Oncorhynchus mykiss* to luteinizing hormone releasing hormone analogue. Aquaculture 166(1–2):163–177

Pankhurst NW, Van Der Kraak G (2000) Evidence that acute stress inhibits ovarian steroidogenesis in rainbow trout in vivo, through the action of cortisol. Gen Comp Endocrinol 117(2):225–237

Pankhurst NW, Van Der Kraak G, Peter RE (1995) Evidence that the inhibitory effects of stress on reproduction in teleost fish are not mediated by the action of cortisol on ovarian steroidogenesis. Gen Comp Endocrinol 99(3):249–257

Pankhurst NW, Purser GJ, Van Der Kraak G et al (1996) Effect of holding temperature on ovulation, egg fertility, plasma levels of reproductive hormones and in vitro ovarian steroidogenesis in the rainbow trout *Oncorhynchus mykiss*. Aquaculture 146(3–4):277–290

Paullada-Salmerón JA, Loentgen GH, Cowan M et al (2017) Developmental changes and day-night expression of the gonadotropin-inhibitory hormone system in the European sea bass: effects of rearing temperature. Comp Biochem Physiol A Mol Integr Physiol 206:54–62

Perry AN, Grober MS (2003) A model for social control of sex change: interactions of behavior, neuropeptides, glucocorticoids, and sex steroids. Horm Behav 43(1):31–38

Pickering AD, Pottinger TG, Carragher J et al (1987) The effects of acute and chronic stress on the levels of reproductive hormones in the plasma of mature male brown trout, *Salmo trutta* L. Gen Comp Endocrinol 68(2):249–259

Piferrer F, Blázquez M, Navarro L et al (2005) Genetic, endocrine, and environmental components of sex determination and differentiation in the European sea bass (*Dicentrarchus labrax* L.). Gen Comp Endocrinol 142(1–2):102–110

Plattner H, Verkhratsky A (2016) Inseparable tandem: evolution chooses ATP and Ca2+ to control life, death and cellular signalling. Philos Trans R Soc Lond B Biol Sci 371(1700):20150419

Pörtner HO, Farrell AP (2008) Physiology and climate change. Science 322(5902):690–692

Pörtner HO, Karl DM, Boyd PW (2014) Ocean systems. In: Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 411–484

Raff H, Bruder ED (2006) Steroidogenesis in human aldosterone-secreting adenomas and adrenal hyperplasias: effects of hypoxia in vitro. Am J Physiol Endocrinol Metab 290(1):E199–E203

Rahman MS, Morita M, Takemura A et al (2003) Hormonal changes in relation to lunar periodicity in the testis of the forktail rabbitfish, *Siganus argenteus*. Gen Comp Endocrinol 131(3):302–309

Robertson DR (1972) Social control of sex reversal in a coral-reef fish. Science 177(4053): 1007–1009

Rodríguez L, Zanuy S, Carrillo M (2001) Influence of daylength on the age at first maturity and somatic growth in male sea bass (Dicentrarchus labrax, L.). Aquaculture 196(1–2):159–175

Rombough PJ (1988) Respiratory gas exchange, aerobic metabolism, and effects of hypoxia during early life. In: Fish physiology, vol 11. Academic Press, Cambridge, pp 59–161

Rombough PJ (1997) The effects of temperature on embryonic and larval development. In: Seminar series-society for experimental biology, vol 61. Cambridge University Press, Cambridge, pp 177–224

Ross RM (1987) Sex-change linked growth acceleration in a coral-reef fish, *Thalassoma duperrey*. J Exp Zool 244(3):455–461

Ruensirikul J, Chiayvareesajja S (2020) Effects of water salinity on reproductive performance of the female hatchery-reared spotted scat, *Scatophagus argus* (Linnaeus, 1766) broodstock. Songklanakarin J Sci Technol 42(1):95–100

Saha N, Koner D, Sharma R (2022) Environmental hypoxia: a threat to the gonadal development and reproduction in bony fishes. Aquacult Fisheries. https://doi.org/10.1016/j.aaf.2022.02.002

Saillant E, Fostier A, Haffray P et al (2003) Saline preferendum for the European sea bass, *Dicentrarchus labrax*, larvae and juveniles: effect of salinity on early development and sex determination. J Exp Mar Biol Ecol 287(1):103–117

Sampaio LA, Bianchini A (2002) Salinity effects on osmoregulation and growth of the euryhaline flounder *Paralichthys orbignyanus*. J Exp Mar Biol Ecol 269(2):187–196

Schade FM, Clemmesen C, Mathias Wegner K (2014) Within-and transgenerational effects of ocean acidification on life history of marine three-spined stickleback (*Gasterosteus aculeatus*). Mar Biol 161(7):1667–1676

Schreck CB, Olla BL, Davis MW (1997) Behavioural responses to stress. Fish Stress Health Aquacult 62:145–170

Schreck CB, Contreras-Sanchez W, Fitzpatrick MS (2001) Effects of stress on fish reproduction, gamete quality, and progeny. In: Reproductive biotechnology in Finfish aquaculture. Elsevier, pp 3–24

Schulte PM, Healy TM, Fangue NA (2011) Thermal performance curves, phenotypic plasticity, and the time scales of temperature exposure. Integr Comp Biol 51(5):691–702

Schunter C, Welch MJ, Ryu T et al (2016) Molecular signatures of transgenerational response to ocean acidification in a species of reef fish. Nat Clim Chang 6(11):1014–1018

Scott AP (1987) Reproductive endocrinology of fish. In: Fundamentals of comparative vertebrate endocrinology. Springer, Boston, MA, pp 223–256

Servili A, Lethimonier C, Lareyre JJ et al (2010) The highly conserved gonadotropin-releasing hormone-2 form acts as a melatonin-releasing factor in the pineal of a teleost fish, the European sea bass *Dicentrarchus labrax*. Endocrinology 151(5):2265–2275

Servili A, Canario A, Mouchel O et al (2020) Climate change impacts on fish reproduction are mediated at multiple levels of the brain-pituitary-gonad axis. Gen Comp Endocrinol 291: 113439. https://doi.org/10.1016/j.ygcen.2020.113439

Shang EH, Wu RS (2004) Aquatic hypoxia is a teratogen and affects fish embryonic development. Environ Sci Technol 38(18):4763–4767

Shields RJ, Brown NP, Bromage NR (1997) Blastomere morphology as a predictive measure of fish egg viability. Aquaculture 155(1–4):1–12

Simensen LM, Jonassen TM, Imsland AK et al (2000) Photoperiod regulation of growth of juvenile Atlantic halibut (*Hippoglossus hippoglossus* L.). Aquaculture 190(1–2):119–128

Skov C, Brodersen J, Brönmark C et al (2005) Evaluation of PIT-tagging in cyprinids. J Fish Biol 67(5):1195–1201

Solomon-Lane TK, Crespi EJ, Grober MS (2013) Stress and serial adult metamorphosis: multiple roles for the stress axis in socially regulated sex change. Front Neurosci 7:210

Soria FN, Strüssmann CA, Miranda LA (2008) High water temperatures impair the reproductive ability of the pejerrey fish *Odontesthes bonariensis*: effects on the hypophyseal-gonadal axis. Physiol Biochem Zool 81(6):898–905

Stoss J (1983) Fish gamete preservation and Spermatozoan physiology. Fish Physiol 9:305–350

Strüssmann CA, Saito T, Usui M et al (1997) Thermal thresholds and critical period of thermolabile sex determination in two atherinid fishes, *Odontesthes bonariensis* and *Patagonina hatcheri*. J Exp Zool 278(3):167–177

Strüssmann CA, Conover DO, Somoza GM, Miranda LA (2010) Implications of climate change for the reproductive capacity and survival of New World silversides (family Atherinopsidae). J Fish Biol 77(8):1818–1834

Sullivan CM (1954) Temperature reception and responses in fish. J Fish Res Board Can 11(2): 153–170

Suwa K, Yamashita M (2007) Regulatory mechanisms of oocyte maturation and ovulation. In: The fish oocyte. Springer, Dordrecht, pp 323–347

Takemura A, Susilo ES, Rahman MS et al (2004) Perception and possible utilization of moonlight intensity for reproductive activities in a lunar-synchronized spawner, the golden rabbitfish. J Exp Zool A Comp Exp Biol 301(10):844–851

Tamaru CS, Lee CS, Kelley CD et al (1994) Oocyte growth in the striped mullet *Mugil cephalus* L. maturing at different salinities. J World Aquacult Soc 25(1):109–115

Thomas P, Rahman MS (2012) Extensive reproductive disruption, ovarian masculinization and aromatase suppression in Atlantic croaker in the northern Gulf of Mexico hypoxic zone. Proc R Soc B Biol Sci 279(1726):28–38

Thomas P, Rahman MS, Kummer JA et al (2006) Reproductive endocrine dysfunction in Atlantic croaker exposed to hypoxia. Mar Environ Res 62:S249–S252

Thomas P, Rahman MS, Khan IA et al (2007) Widespread endocrine disruption and reproductive impairment in an estuarine fish population exposed to seasonal hypoxia. Proc R Soc B Biol Sci 274(1626):2693–2702

Thomas G, Lorenz AW, Sundermann A et al (2015) Fish community responses and the temporal dynamics of recovery following river habitat restorations in Europe. Freshw Sci 34(3):975–990

Trudeau VL, Sloley BD, Wong AOL et al (1993) Interactions of gonadal steroids with brain dopamine and gonadotropin-releasing hormone in the control of gonadotropin-II secretion in the goldfish. Gen Comp Endocrinol 89(1):39–50

Tveiten H (2008) Temperature influence on reproductive development and gamete quality in Atlantic cod (*Gadus morhua)*. Cybium 32(2 Suppl):195

Tveiten H, Solevåg SE, Johnsen HK (2001) Holding temperature during the breeding season influences final maturation and egg quality in common wolffish. J Fish Biol 58(2):374–385

Van Der Kraak G, Pankhurst NW (1997) Temperature effects on the reproductive performance of fish. In: Wood CM, McDonald DG (eds) global warming: implications for freshwater and marine fish, pp 159–176

Von Ihering R (1937) A method for inducing fish to spawn. Progr Fish Culturist 4(34):15–16

Wang N, Teletchea F, Kestemont P, Milla S, Fontaine P (2010) Photothermal control of the reproductive cycle in temperate fishes. Rev Aquac 2(4):209–222

Wang SY, Lau K, Lai KP et al (2016) Hypoxia causes transgenerational impairments in reproduction of fish. Nat Commun 7:12114. https://doi.org/10.1038/ncomms12114

Watts M, Pankhurst NW, King HR (2004) Maintenance of Atlantic salmon (*Salmo salar*) at elevated temperature inhibits cytochrome P450 aromatase activity in isolated ovarian follicles. Gen Comp Endocrinol 135(3):381–390

Westin L, Nissling A (1991) Effects of salinity on spermatozoa motility, percentage of fertilized eggs and egg development of Baltic cod (*Gadus morhua*), and implications for cod stock fluctuations in the Baltic. Mar Biol 108(1):5–9

Westring CG, Ando H, Kitahashi T et al (2008) Seasonal changes in CRF-I and urotensin I transcript levels in Masu salmon: correlation with cortisol secretion during spawning. Gen Comp Endocrinol 155(1):126–140

Wu RS (2009) Effects of hypoxia on fish reproduction and development. In: Fish physiology, vol 27. Academic Press, Cambridge, MA, pp 79–141

Wu RS, Zhou BS, Randall DJ et al (2003) Aquatic hypoxia is a disrupter and impairs fish reproduction. Environ Sci Technol 37(6):137–1141. https://doi.org/10.1021/es0258327

Yamaguchi H, Mizushima K, Sakamoto S et al (2010) Effects of temperature, salinity and irradiance on growth of the novel red tide flagellate *Chattonella ovata* (Raphidophyceae). Harmful Algae 9(4):398–401

Yeganeh S, Amiri BM, Alavi SMH (2008) Motility of *Mugil cephalus* L. spermatozoa in coelomic fluid, seminal fluid and saline media. J Appl Ichthyol 24(4):517–518

Zanuy S, Carrillo M (1985) Annual cycles of growth, feeding rate, gross conversion efficiency and hematocrit levels of sea bass (*Dicentrarchus labrax* L.) adapted to two different osmotic media. Aquaculture 44(1):11–12

Zanuy S, Carrillo M, Ruiz F (1986) Delayed gametogenesis and spawning of sea bass (Dicentrarchus labrax L.) kept under different photoperiod and temperature regimes. Fish Physiol Biochem 2(1):53–63

Zilli L, Schiavone R, Zonno V, Storelli C, Vilella S (2004) Adenosine triphosphate concentration and β-d-glucuronidase activity as indicators of sea bass semen quality. Biol Reprod 70(6): 1679–1684

Zohar Y, Mylonas CC (2001) Endocrine manipulations of spawning in cultured fish: from hormones to genes. In: Reproductive biotechnology in Finfish aquaculture. Elsevier, Amsterdam, pp 99–136

Impact of Climate Change on Fish Reproduction and Climate-Resilient Broodstock Management

Alexander Ciji and Md. Shahbaz Akhtar

Abstract

The reproductive activities and early life stages in most fishes are being affected by increasing water temperature and other environmental disturbances associated with climate change. In this chapter, we have taken an in-depth assessment of current literature on the impacts of climate change on fish broodstock and their reproductive performance and discussed various strategies for climate-resilient broodstock management.

Keywords

Fish reproduction · Climate change · Broodstock management · Dietary interventions · Culture practice

1 Introduction

Climate change is a serious threat to the aquatic environment as it alters the physical and chemical characteristics of the water. Reproduction (both timing and duration as well as success and reproductive output) in most organisms, including fish, is known to be affected by environmental fluctuations linked with climate change and global warming; hence altered reproduction could be the primary cause of climate change-driven population declines (Miller et al. 2015). The main harmful effect of climate change appears to be elevated water temperature, which has been shown to affect different stages of reproductive processes, including gamete formation, maturation, spawning, fertilization, embryonic development, hatching, and finally growth and

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survival (Pankhurst and Munday 2011). Temperature is the primary regulatory factor in fish and controls all reproductive processes (Pankhurst and Munday 2011). In mature fishes, the temperature has a major role in synchronizing the final stages of reproductive maturity and also in truncating reproductive episodes (Pankhurst and Porter 2003). The elevated temperatures are reported to delay the onset of maturation and ovulation in autumn-spawning fish species (Pankhurst and King 2010). Temperature, however, has an important function in the modulation of post-fertilization processes through its rate-determining impacts on ontogeny (Pauly and Pullin 1988) and subsequent larval development (Howell et al. 1998). In short, the environmental changes associated with climate change affect not only fish broodstocks and gametes but also their offspring/progeny.

2 Consequences of Climate Change-Induced Environmental Changes on Fish Broodstock

The water temperature spikes associated with climate change appear to influence important biological functions such as reproduction, with the gonads being one of the organs most affected (Miranda et al. 2013). The climate change-induced changes in water parameters seem to influence the reproductive behavior and gamete quality of fish (Servili et al. 2020). The reproductive cycle of most fishes in temperate and cold climates is primarily controlled by rhythmic temperature and, or photoperiod, that regulate the spawning time to coincide with the favorable period for offspring survival (Bromage et al. 2001; Portner and Farrell 2008). While, in tropical and subtropical fishes, reproductive activity is triggered by temperature and rainfall. Hence, the water temperature can exert a stronger influence on reproduction in terms of the reproductive season, timing, and duration, as well as reproductive output (Durant et al. 2007). Seasonal change in water temperature has either fastened or delayed the spawning process depending upon the species and their spawning window. For instance, increasing temperatures stimulate maturation and spawning in spring-spawners, whereas decreasing temperatures stimulate reproduction in autumn spawning species, and hence higher water temperatures are reported to truncate spring spawning and delay autumn spawning (Pankhurst and Munday 2011). In extreme cases, the breeding season could be lost completely (Elisio et al. 2012). Several traits in adult fish, including development rate, maturity age, and migration timing respond to thermal cues (Hovel et al. 2017). In fish with temperature-dependent sex determination, an individual's phenotypic sex is decided partly or completely by the temperature encountered during gonadal sex differentiation, with high temperatures causing germ cell degeneration and lower fertility (Strussmann et al. 2010). High temperature has a masculinizing effect, and therefore, exposure to elevated temperature during critical periods in early life usually leads to an increase in the number of males (Ospina-Alvarez and Piferrer 2008; Ribas et al. 2017). Navarro-Martín et al. (2011) reported inhibition of aromatase expression at higher temperatures due to the methylation of the gonadal *cyp19a1a* gene leading to masculinization of genotypic females. Also, a higher temperature was reported to decrease the transcription of the gonadotrophin-inhibitory hormone as well as its receptor, adversely affecting gonadal steroidogenesis (Piferrer et al. 2005; Paullada-Salmerón et al. 2017; Servili et al. 2020).

Hypoxia is another consequence of climate change, also decreasing fish growth and feeding, reducing gonadal development and gamete production in both males and females, and thereby indirectly affecting reproduction (Lai et al. 2016; Thomas and Rahman 2010; Wu et al. 2003). More precisely, hypoxia can affect oocyte and sperm maturation (or maturational competence), which is necessary to obtain fertile gametes (Servili et al. 2020). Gonad masculinization and biased sex ratio are demonstrated in fish exposed to hypoxia (Shang et al. 2006). Being an endocrine disruptor, hypoxia impairs reproduction and hence the sustainability of the fish population (Wu et al. 2003). Other major variables that are expected to affect gamete quality and reproductive output in fish are water salinity and pH (elevated PCO_2 or acidification) (Servili et al. 2020). The severity of climate change-related disturbances in water quality on reproduction depends on factors such as physiological tolerances of the species, the ability for acclimatization and adaptation, behavioral avoidance potential, ability to extend or shift ranges, and the timing and duration of challenges faced in relation to the reproductive phase (Pankhurst and Munday 2011).

3 The Climate Change-Induced Environmental Changes on Fish Eggs/Larvae/Juveniles

Water temperature has a critical role in post-fertilization processes (Pankhurst and Munday 2011) as it determines the embryonic duration and hatching time (Pauly and Pullin 1988) and later larval development, growth, and survival (Howell et al. 1998; Jobling 1997; Sponaugle and Cowen 1996). The temperature tolerance limits of most fish species eggs seem to be within ± 6 °C of the spawning temperature (Rombough 1997) and small temperature rises can drastically increase egg mortality, particularly in tropical species (Gagliano et al. 2007). Water temperature influences egg survival and embryonic duration, hatching size, developmental rate, larval duration, growth, and survival. Perhaps, fish eggs and larvae are more vulnerable to temperature, oxygen, and pH changes in the environment than adults. The higher surface-to-volume ratio and dearth of functional acid-base regulatory systems make them more vulnerable (Ishimatsu et al. 2008; Kikkawa et al. 2003; Servili et al. 2020). Further, hypoxic conditions are reported to cause growth retardation, delayed development, and increased malformation during early life stages in fish (Rombough 1988). Lastly, changes in plankton/prey species composition related to climate change will alter the food web, adversely affecting the growth and survival of early life stages (Servili et al. 2020). In short, the thermal regime experienced during embryonic development, influenced by climate change, would affect larvae and juveniles' growth and fitness (Alami-Durante et al. 2007). The major effects of climate change-induced environmental changes on fish reproduction are depicted in Fig. 1.

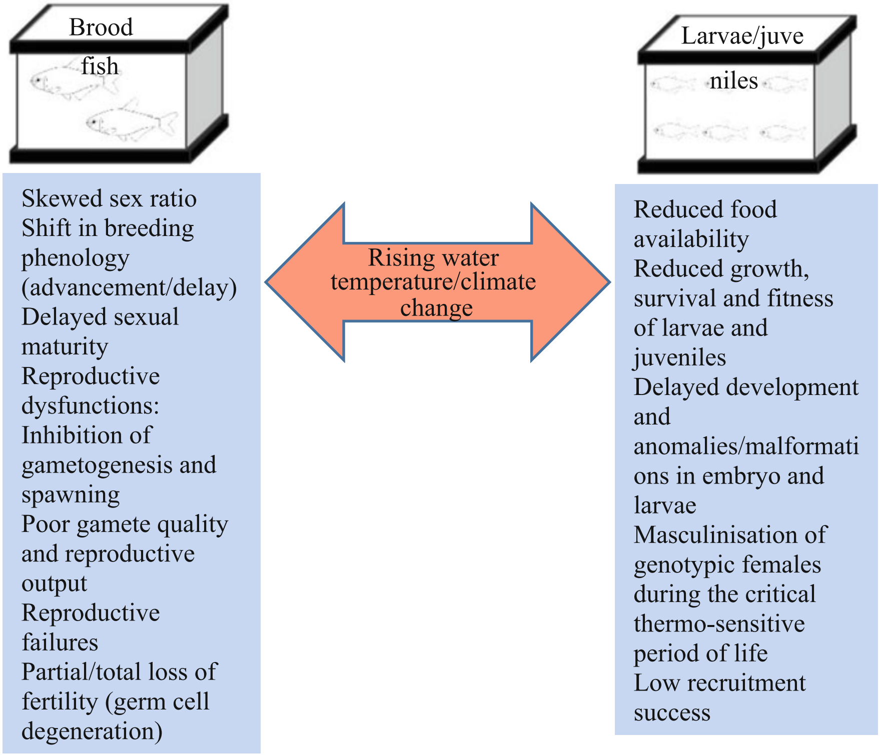

Fig. 1 A schematic illustration of the major effects of climate change-induced environmental changes on fish reproduction

4 Climate-Resilient Broodstock Management Strategies

Farmers and other aquaculture stakeholders may be able to play a vital role in minimizing the consequences of climate change by modifying their cultural practices to reduce greenhouse gas (GHG) emissions. This may include the use of environment-friendly culture practices and technologies to reduce air and water pollution, such as solar energy, efficient feeding, and wastewater/effluent management techniques (Vgreen 2012; Barange et al. 2018). Adaptation aims to increase resilience to the repercussions and the ability to use new opportunities in a sustainable and ethical manner. It can include technical changes, changes in resource users/producer's behavior, and modifications in the governance system (Lorenzen et al. 2017). Adaptation is currently recognized as the most viable approach for dealing with the consequences of climate change on aquaculture (Yazdi and Shakouri 2010). The various mitigation and adaptation strategies are discussed hereunder.

4.1 Better Broodstock Feeds and Feed Management

Many diverse ingredients of vegetable, marine, and land animal origin are used in aquaculture feeds, and the primary production of these feed ingredients is linked to a number of sustainability issues. Ingredient source and feed management in aquaculture will be affected by climate change. When greenhouse gas emissions (GHG) arising from fishmeal and fish oil production (the major protein and lipid source in broodstock diets), feed manufacturing, and transport are taken into account, fish feed accounts for the bulk of GHG emissions from aquaculture. Therefore, feeds and feeding practices that help farmers to boost production/performance, support animal health or end-product quality, and minimize environmental footprint are the need of the hour. In short, different raw materials used in the fish feed industry should be economically and environmentally sustainable. Both fishmeal and fish oil are limited resources that are shared among an array of users, including direct human consumption, aquaculture, and the farm animal industry.

The incorporation of feed protein sources that are climate-smart and nutritionally balanced will support broodstock development and sustainable growth of aquaculture. The use of microbial and insect-based protein and oil sources should be encouraged. However, the significance of marine raw materials in providing critical nutrients for optimum reproductive performance (optimal gametogenesis, spawning success, egg/larvae quality and their survival, and eventually the performance of a hatchery) cannot be ignored. Therefore, the effect of reducing the inclusion of fishmeal and fish oil in broodstock diets on egg and larvae production should be thoroughly investigated. At the same time, the potential impacts of diets with increased quantities of plant meals and oils on egg quality and larval production should be ascertained before developing climate-smart broodstock feed formulations. Studies showed that supplementation of specific nutrients such as selenium in plant-based broodstock diets improved reproductive performance and offspring quality (Wischhusen et al. 2019). Nevertheless, nutritional programming through broodstock diets has shown to enhance the utilization of low fishmeal and fish oil diets by their progeny (Izquierdo et al. 2015), supporting sustainable aquaculture. Further, the stress (climate and other anthropogenic stressors) resilience of the broodstock can be improved through dietary interventions of nutritive and non-nutritive compounds/additives as prophylactic measures.

4.2 Development of Climate-Resilient Broodstock and Rearing Systems

To maintain fish biodiversity, it is necessary to create measures that can mitigate the negative consequences of future climate change-induced temperature rises. Shifting to less vulnerable or more resilient species to climate change through selective breeding or thermal programming during early life stages can be taken as an adaptation strategy. It is noteworthy to mention that in several species, the thermal history of parents/broodstock as well as thermal programming during early life stages (rearing at elevated temperature) is known to improve performance at high temperatures (Rombough 1997; Pankhurst and Munday 2011). The use of a climate-smart fish broodstock pond is highly advisable. Broodstock rearing in a biofloc system with zero or minimal water exchange is a sustainable and viable alternative as the microbial aggregates of the biofloc serve as natural food, reducing the supplementary feed requirement. Furthermore, biofloc enhances gonadal development and spawning performance of fish broodstock (Ogello et al. 2021). Recent studies demonstrated enhanced reproductive performance and offspring quality of shrimp broodstock reared under biofloc (Chim et al. 2010; Cardona et al. 2016). This improvement in reproductive performance could be attributed to additional energy from biofloc aggregates (Chim et al. 2010), or the presence of growth-enhancing factors in biofloc (Wasielesky et al. 2006; Xu et al. 2012), and/or its ability to improve the immune and antioxidant response (Ju et al. 2008; Xu and Pan 2013). Also, biofloc can be used for the mass production of live food organisms such as rotifers, copepods, cladocerans, and Artemia which are crucial for larviculture in hatcheries (Ogello et al. 2021). Moreover, the biofloc paste can be utilized as an enrichment emulsion for live food and larval fish, reducing the need for expensive commercial enrichment emulsions (Ogello et al. 2021). The presence of nutritious compounds such as essential PUFAs in biofloc meals made it a feed ingredient in local hatcheries as a substitute for expensive fishmeal (Ogello et al. 2018, 2021). Aquaponics, which connects fish production with soil-less plant production in recirculating systems, provides an additional strategy, whereby outputs from one subsystem become inputs to another, enhancing water productivity. The rearing of broodstock in recirculating aquaculture systems can be adopted to increase water savings (Otoshi et al. 2003; Liu et al. 2021). Similarly, captive maturation of brooders using gravel-bed biofilters (Akhtar et al. 2018) can be explored to minimize water use.

4.3 Development of Climate-Resilient Hatching and Nursery Rearing Systems

Setting up artificial shades in hatcheries without compromising fitness or hatching success is a very useful and simple tool to overcome highly skewed sex ratios reported in several fish species in the face of higher temperatures related to climate change. Further, the climate change-related water temperature fluctuations in hatcheries and nursery rearing systems can be minimized by infrastructure investment in temperature control systems (Migaud et al. 2013), removing or minimizing other manmade stressors so that fish can adapt to climate change more effectively.

4.4 Climate-Induced Stress Mitigation by Dietary Interventions

Some effects of climate change on fish may be unavoidable; however, certain resilience and mitigation methods can mitigate their severity. Dietary intervention to reduce several climate-induced stresses in fish is one of the feasible techniques (Ciji and Akhtar 2021). According to studies, certain dietary supplements can activate defensive mechanisms in stressed fish, hence reverse the negative consequences of stress (Manush et al. 2005; Sarma et al. 2009; Akhtar et al. 2010, 2012). High-protein diets have ameliorative effects against many stresses (Sarma et al. 2009). L-tryptophan has also been observed to alleviate heat stress in numerous fish species (Ciji and Akhtar 2021; Akhtar et al. 2010). Ciji et al. (2013a) demonstrated that dietary vitamin E is effective in reducing nitrite stress in juvenile *L. rohita*. Dietary vitamin E and L-tryptophan were also found to restore the sex steroids and thyroid hormones in nitrite-exposed *L. rohita* juveniles (Ciji et al. 2013b; Ciji and Akhtar 2020). Alternatively, dietary pyridoxine supplementation was reported to have growth-enhancing, stress-reducing, and immunomodulatory effects in temperature-exposed *L. rohita* fingerlings (Akhtar et al. 2012). In other words, the effects of climate-induced stressors can be mitigated by producing customized broodstock diets that include supplements for stress mitigation.

5 Conclusion

We should be ready to confront the threats that climate change imposes. It is already impairing the reproduction and early life stages of fish. For sustainable aquaculture, robust climate-friendly broodstock management systems must be developed. In order to evaluate the effects of climate change on broodstock, future research should attempt to comprehend the mechanism of temperature interaction with multiple stressors and to identify potential countermeasures. The dietary interventions for fish stress management as a consequence of climate change are a promising adaptation strategy. To establish a holistic nutritional model to mitigate or adapt to the impact of climate change, future research is required, particularly in multiple stress-mitigating strategies. Furthermore, the development of climate-resilient broodstock through thermal programming can be promising.

References

Akhtar MS, Pal AK, Sahu NP, Alexander C, Gupta SK, Choudhary AK et al (2010) Stress mitigating and immuno-modulatory effect of dietary pyridoxine in *Labeo rohita* (Hamilton) fingerlings. Aquacult Res 41(7):991–1002

Akhtar MS, Pal AK, Sahu NP, Ciji A, Meena DK (2012) Effects of dietary pyridoxine on growth and physiological responses of *Labeo rohita* fingerlings reared at higher water temperature. Isr J Aquacult Bamidgeh IJA-64:777

Akhtar MS, Rajesh M, Ciji A, Sharma P, Kamalam BS, Patiyal RS, Singh AK, Sarma D (2018) Photo-thermal manipulations induce captive maturation and spawning in endangered golden mahseer (Tor putitora): a silver-lining in the strangled conservation efforts of decades. Aquaculture 497:336–347

Alami-Durante H, Olive N, Rouel M (2007) Early thermal history significantly affects the seasonal hyperplastic process occurring in the myotomal white muscle of *Dicentrarchus labrax* juvenile. Cell Tissue Res 327:553–570

Barange M, Bahri T, Beveridge MCM, Cochrane AL, Funge-Smith S, Paulain F (2018) Impacts of climate change on fisheries and aquaculture, synthesis of current knowledge, adaptation and mitigation options. FAO, Rome

Bromage N, Porter M, Randall C (2001) The environmental regulation of maturation in farmed finfish with special reference to the role of photoperiod and melatonin. Aquaculture 197:63–98

Cardona E, Lorgeoux B, Chim L, Goguenheim J, Le Delliou H, Cahu C (2016) Biofloc contribution to antioxidant defence status, lipid nutrition and reproductive performance of broodstock of the shrimp *Litopenaeus stylirostris*: consequences for the quality of eggs and larvae. Aquaculture 452:252–262

Chim L, Huber M, Lemaire P, Brun P, Goguenheim J (2010) Floc culture system applied for intensive broodstock farming of the blue shrimp *Litopenaeus stylirostris*: first trial carried out in New Caledonia. EAS Aquaculture Europe 2010. In book of abstract

Ciji A, Akhtar MS (2020) Nitrite implications and its management strategies in aquaculture: a review. Rev Aquac 12:878–908

Ciji A, Akhtar MS (2021) Stress management in aquaculture: a review of dietary interventions. Rev Aquac 13:2190–2247. https://doi.org/10.1111/raq.12565

Ciji A, Sahu NP, Pal AK, Akhtar MS (2013a) Physiological changes in *Labeo rohita* during nitrite exposure: detoxification through dietary vitamin E. Comp Biochem Physiol C 158:122–129

Ciji A, Sahu NP, Pal AK, Akhtar MS (2013b) Nitrite-induced alterations in sex steroids and thyroid hormones of *Labeo rohita* juveniles: effects of dietary vitamin E and L-tryptophan. Fish Physiol Biochem 39(5):1297–1307

Durant JM, Hjermann DO, Ottersen G, Stenseth NC (2007) Climate and the match or mismatch between predator requirements and resource availability. Climate Res 33:271–283

Elisio M, Chalde T, Miranda LA (2012) Effects of short periods of warm water fluctuations on reproductive endocrine axis of the pejerrey (*Odontesthes bonariensis*) spawning. Comp Biochem Physiol A 163:47–55

Gagliano M, McCormick MI, Meekan MG (2007) Temperature induced shifts in selective pressure at a critical developmental transition. Oecologia 152:219–225. https://doi.org/10.1007/S00442-006-0647-1

Hovel RA, Carlson SM, Quinn TP (2017) Climate change alters the reproductive phenology and investment of a lacustrine fish, the three-spine stickleback. Glob Chang Biol 23:2308–2320

Howell BR, Day OJ, Ellis T, Baynes SM (1998) Early life stages of farmed fish. In: Black KD, Pickering AD (eds) Biology of farmed fish. Sheffield Academic Press, Sheffield, pp 27–66

Ishimatsu A, Hayashi M, Kikkawa T (2008) Fishes in high-CO2, acidified oceans. Mar Ecol Prog Ser 373:295–302. https://doi.org/10.3354/meps07823

Izquierdo MS, Turkmen S, Montero D, Zamorano MJ, Afonso JM, Karalazos V, Fernández-Palacios H (2015) Nutritional programming through broodstock diets to improve utilization of very low fishmeal and fish oil diets in gilthead sea bream. Aquaculture 449:18–26

Jobling M (1997) Temperature and growth: modulation of growth rate via temperature change. In: Wood CM, McDonald DG (eds) Global warming: implications for freshwater and marine fish. Cambridge University Press, Cambridge, pp 225–253

Ju Z, Forster I, Conquest L, Dominy W (2008) Enhanced growth effects on shrimp (*Litopenaeus vannamei*) from inclusion of whole shrimp floc or floc fractions to a formulated diet. Aquacult Nutr 14(6):533–543

Kikkawa T, Ishimatsu A, Kita J (2003) Acute CO2 tolerance during the early developmental stages of four marine teleosts. Environ Toxicol 18:375–382. https://doi.org/10.1002/tox.10139

Lai KP, Li JW, Tse AC, Cheung A, Wang S, Chan TF, Kong RY, Wu RS (2016) Transcriptomic responses of marine medaka's ovary to hypoxia. Aquat Toxicol 177:476–483

Liu Q, Zheng Y, Fu L, Simco BA, Goudie CA (2021) Brood-stock management and natural spawning of American shad (*Alosa sapidissima*) in a recirculating aquaculture system. Aquaculture 532:735952

Lorenzen K, Ainsworth CH, Baker SM, Barbieri LR, Camp EV, Dotson JR et al (2017) Climate change impacts on Florida's fisheries and aquaculture sectors and options for adaptation. In:

Florida's climate: changes, variations, and impacts. Retrieved from: http://purl.flvc.org/fsu/fd/FSU_libsubv1_scholarship_submission_1515510950_127e8200

Manush SM, Pal AK, Das T, Mukherjee SC (2005) Dietary high protein and vitamin C mitigate stress due to chelate claw ablation in *Macrobrachium rosenbergii* males. Comp Biochem Physiol A 142:10–18

Migaud H, Bell G, Cabrita E, McAndrew B, Davie A, Bobe J, Herraez MP, Carrillo M (2013) Gamete quality and broodstock management in temperate fish. Rev Aquac 5(Suppl. 1):S194–S223. https://doi.org/10.1111/raq.12025

Miller GM, Kroon FJ, Metcalfe S, Munday PA (2015) Temperature is the evil twin: effects of increased temperature and ocean acidification on reproduction in a reef fish. Ecol Appl 25(3): 603–620

Miranda LA, Chalde T, Elisio M, Strussmann CA (2013) Effects of global warming on fish reproductive endocrine axis, with special emphasis in pejerrey *Odontesthes bonariensis*. Gen Comp Endocrinol 192:45–54

Navarro-Martín L, Viñas J, Ribas L, Díaz N, Gutiérrez A, Di Croce L, Piferrer F (2011) DNA methylation of the gonadal aromatase (cyp19a) promoter is involved in temperature-dependent sex ratio shifts in the European sea bass. PLoS Genet 12:e1002447

Ogello EO, Wullur S, Sakakura Y, Hagiwara A (2018) Composting fishwastes as low-cost and stable diet for culturing *Brachionus rotundiformis* Tschugunoff (Rotifera): influence on water quality and microbiota. Aquaculture 486:232–239

Ogello EO, Outa NO, Obiero KO, Kyule DN, Munguti JM (2021) The prospects of biofloc technology (BFT) for sustainable aquaculture development. Sci Afr 14:e01053

Ospina-Alvarez N, Piferrer F (2008) Temperature-dependent sex determination in fish revisited: prevalence, a single sex ratio response pattern, and possible effects of climate change. PLoS One 3(7):e2837. https://doi.org/10.1371/journal.pone.0002837

Otoshi CA, Arce SM, Moss SM (2003) Growth and reproductive performance of broodstock shrimp reared in a biosecure recirculating aquaculture system versus a flow-through pond. Aquacult Eng 29:93–107

Pankhurst NW, King HR (2010) Temperature and salmonid reproduction: implications for aquaculture. J Fish Biol 76:69–85. https://doi.org/10.1111/J.1095-8649.2009.02484.X

Pankhurst NW, Munday PL (2011) Effects of climate change on fish reproduction and early life history stages. Mar Freshw Res 62:1015–1026

Pankhurst NW, Porter MJR (2003) Cold and dark or warm and light: variations on the theme of environmental control of reproduction. Fish Physiol Biochem 28:385–389. https://doi.org/10.1023/B:FISH.0000030602.51939.50

Paullada-Salmerón JA, Loentgen GH, Cowan ME, Aliaga-Guerrero M, Rendón-Unceta MC, Muñoz-Cueto JA (2017) Developmental changes and day–night expression of the gonadotropininhibitory hormone system in the European sea bass: effects of rearing temperature. Comp Biochem Physiol A 206:54–62

Pauly D, Pullin RSV (1988) Hatching time in spherical pelagic marine eggs in response to temperature and egg size. Environ Biol Fishes 22:261–271. https://doi.org/10.1007/BF00004892

Piferrer F, Blazquez M, Navarro L, Gonzalez A (2005) Genetic, endocrine, and environmental components of sex determination and differentiation in the European sea bass (*Dicentrarchus labrax* L.). Gen Comp Endocrinol 142:102–110. https://doi.org/10.1016/j.ygcen.2005.02.011

Portner HO, Farrell AP (2008) Physiology and climate change. Science 322:690

Ribas L, Liew WC, Diaz N, Sreenivasan R, Orban L, Piferrer F (2017) Heat-induced masculinization in domesticated zebrafish is family-specific and yields a set of different gonadal transcriptomes. Proc Natl Acad Sci 114:E941–E950

Rombough PJ (1988) Respiratory gas exchange, aerobic metabolism, and effects of hypoxia during early life. In: Hoar WS, Randall DJ (eds) Fish physiology. Academic Press, San Diego, CA, pp 59–161

Rombough PJ (1997) The effects of temperature on embryonic and larval development. In: Wood CM, McDonald DG (eds) Global warming: implications for freshwater and marine fish. Cambridge University Press, Cambridge, pp 177–223

Sarma K, Pal AK, Sahu NP, Ayyappan S, Baruah K (2009) Dietary high protein and vitamin C mitigates endosulfan toxicity in the spotted murrel, *Channa punctatus* (Bloch, 1793). Sci Total Environ 407:3668–3673

Servili A, Canario AVM, Mouchel O, Munoz-Cueto JA (2020) Climate change impacts on fish reproduction are mediated at multiple levels of the brain-pituitary-gonad axis. Gen Comp Endocrinol 291:113439

Shang EH, Yu RM, Wu RS (2006) Hypoxia affects sex differentiation and development, leading to a male-dominated population in zebrafish (*Danio rerio*). Environ Sci Technol 40:3118–3122

Sponaugle S, Cowen RK (1996) Larval supply and patterns of recruitment for two Caribbean reef fishes, *Stegastes partitus* and *Acanthurus bahianus*. Mar Freshw Res 47:433–447. https://doi.org/10.1071/MF9960433

Strussmann CA, Conover DO, Somoza GM, Miranda LA (2010) Implications of climate change for the reproductive capacity and survival of New World silversides (family *Atherinopsidae*). J Fish Biol 77:1818–1834

Thomas P, Rahman MS (2010) Region-wide impairment of Atlantic croaker testicular development and sperm production in the northern Gulf of Mexico hypoxic dead zone. Mar Environ Res 69 (Suppl):S59–S62

Vgreen (2012) Life cycle assessment of fish feeds: case study in Bangladesh. WorldFish/USAID “Feed the Future-Aquaculture Bangladesh and CSISA Projects”. Centre of Excellence on Environment Strategy for GREEN Business (VGREEN). Kasetsart University, Bangkok

Wasielesky W, Atwood H, Stokes A, Browdy CL (2006) Effect of natural production in a zero exchange suspended microbial floc based super-intensive culture system for white shrimp *Litopenaeus vannamei*. Aquaculture 25:396–403

Wischhusen P, Parailloux M, Geraert PA, Briens M, Bueno M, Mounicou S, Bouyssiere B, Prabhu PAJ, Kaushik SJ, Fauconneau B, Fontagne-Dicharry S (2019) Effect of dietary Se in rainbow trout (*Oncorhynchus mykiss*) broodstock on antioxidant status, its parental transfer and oxidative status in the progeny. Aquaculture 507:126–138. https://doi.org/10.1016/j.aquaculture.2019.04.006

Wu RSS, Zhou BS, Randall DJ, Woo NYS, Lam PKS (2003) Aquatic hypoxia is an endocrine disruptor and impairs fish reproduction. Environ Sci Technol 37:1137–1141

Xu WJ, Pan LQ (2013) Enhancement of immune response and antioxidant status of *Litopenaeus vannamei* juvenile in biofloc-based culture tanks manipulating high C/N ratio of feed input. Aquaculture 412:117–124

Xu WJ, Pan LQ, Sun XH, Huang J (2012) Effects of bioflocs on water quality, and survival, growth and digestive enzyme activities of *Litopenaeus vannamei* (Boone) in zero-water exchange culture tanks. Aquacult Res 44(7):1093–1102

Yazdi SK, Shakouri D (2010) The effects of climate change on aquaculture. Int J Environ Sci Dev 1:378–382. https://doi.org/10.7763/IJESD.2010.V1.73

Nutrition and Environment Interactions in Aquaculture

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Abstract

With the expansion of aquaculture and its increasing role in the global food system, the complex interactions between fish culture systems and the environment have come under intense scrutiny. On one side, environmental factors can influence or constrain aquaculture operations and on the other, aquaculture exerts a wide range and degree of impacts on the surrounding environment. Feeds and feeding practices are a vital cog in this bidirectional relationship between aquaculture systems and the aquatic environment. Particularly, the increasing use of nutrient-dense pelleted feed in modern intensive aquaculture has led to major environmental concerns. Nutrient loading and loss are a function of the production environment, species, system design as well as feed efficiency and composition. Using nutrient mass balance methods and bioenergetic approaches, the waste output from aquaculture facilities can be estimated and predicted. Subsequently, the management and control of aquaculture waste output should begin with changes in diet formulation and feeding strategies. Pivotal advances in feed manufacturing technology have substantially decreased the production of dietary origin waste in aquaculture. Likewise, the application of digital technologies and the use of smart feeding systems are transitioning feed management from an experience-driven to a knowledge-driven process. As the focus on environmental sustainability increases, there is also a greater emphasis on the use of feed resources in a responsible and environmentally efficient manner. This includes limiting the inclusion of fish meal and fish oil sourced from overexploited wild fishes, and increasing the use of novel plant, animal, and micro-organism-based raw materials which have less ecological costs. Life cycle assessments suggest that fish feed and ingredients are critical determinants of the environmental

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impact of aquaculture. Conversely, the impact of environmental changes on the nutritional requirements of fish and the biological efficiency of feed compositions is less understood. Overall, the aquaculture industry should be prepared to reconfigure and respond to newer environmental concerns over time, through innovations in feed and feeding.

Keywords

Fish · Nutrition · Environment · Interaction

1 Introduction

Aquaculture is a fast-growing and important food production system that encompasses the process of breeding, culturing, and harvesting different aquatic organisms in a highly dynamic farming system with intricately linked biological, environmental, economic, and social factors. In 2018, the global aquaculture fish production reached 82.1 million tonnes (valued at USD 250.1 billion), contributing more than half (52%) of the fish and seafood available for human consumption. The world aquaculture scenario is dominated by Asia, particularly China, followed by India which consolidated its second-leading aquaculture producer status with 7.07 million tonnes in 2018, accounting for 8.6% of world aquaculture production and 66% of the total domestic fish production. Nearly 70 percent of the total farmed fish production (57 million tonnes) now comes from fed aquaculture systems (FAO 2020; Fig. 1). According to one estimate, the use of feed-in aquaculture has grown at an average annual rate of 10.3% since 2000 and is expected to reach more than 65 million tonnes. The volume of feed used in aquaculture will continue to increase further as aquaculture production expands to meet the ever-increasing demands of the growing human population (Couture et al. 2019).

2 Aquaculture and Environment

With the expansion of aquaculture and its increasing role in the global food system, the interactions between diverse fish culture systems and the environment have come under intense scrutiny (Edwards 2015). The interaction between aquaculture operations and the environment is diverse, complex, and cannot be generalized. They vary based on the cultured organism, aquaculture practice, and environmental conditions (Iwama 1991). In the bidirectional framework of environmental impact assessment, the influence of the natural environment or ecological setting on aquaculture systems as well as the impact of aquaculture on the surrounding environment is critical for sustainability.

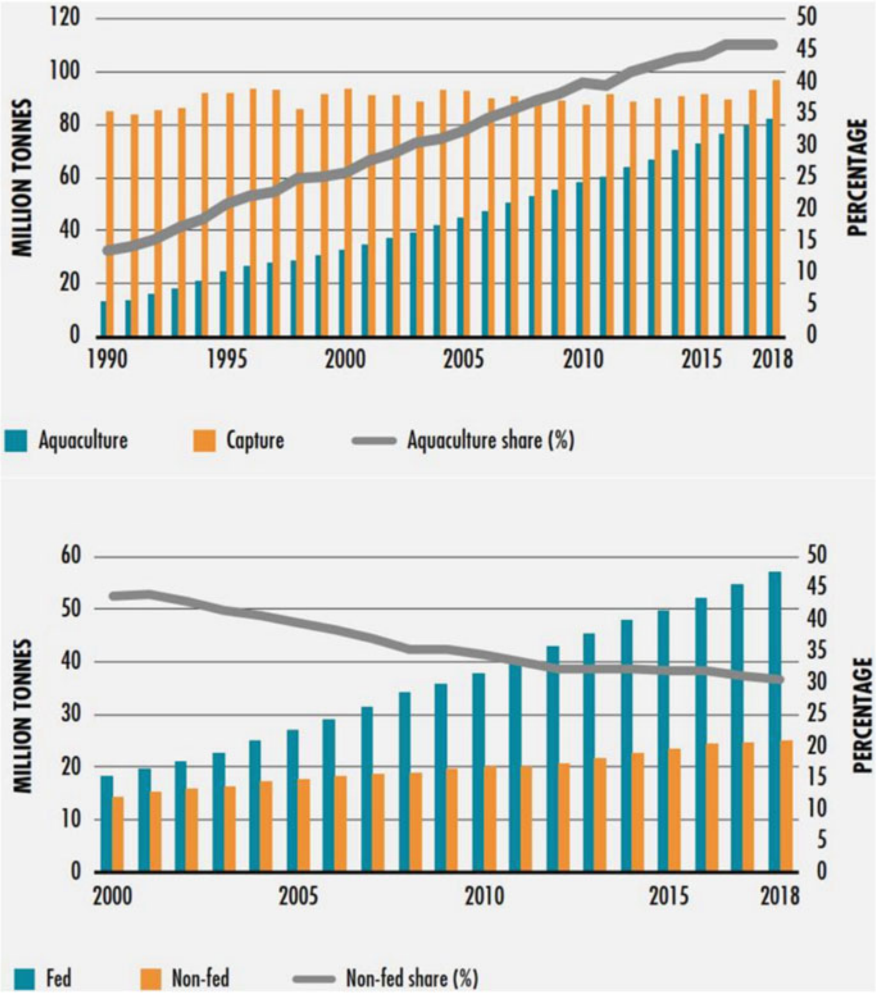

Fig. 1 Share of aquaculture in total fish production and contribution of fed and non-fed aquaculture, 2000–2018. (Source: FAO 2020)

2.1 Effect of Environment on Aquaculture

In aquaculture, the relationship between the cultured animal and its environment is a key factor in a successful operation. Climatic and geographic factors such as temperature, salinity, and hydrodynamics strongly influence aquaculture. Based on optimal growing temperature, cultured finfishes could be categorized as warm water (Indian major carps and tilapia) and coldwater (trout and salmon) species. Likewise, water salinity delineates aquaculture into inland/freshwater, brackish water, and coastal/open ocean aquaculture. As aquaculture is dependent on adequate water supply, year-round culture practices may be constrained by insufficient water during the dry season as well as flooding or excess water during heavy rain. Environmental pollution (pesticides, heavy metals, and microplastics) from agricultural, industrial, and domestic sources can severely constrain aquaculture operations, as resultant stress reduces growth, induces diseases, and causes mortality (Iwama 1991; Edwards 2015). Environmental degradation such as deforestation affects aquaculture through a variety of interlinked effects. For instance, deforestation increases siltation and contributes to unstable water regimes which adversely impacts aquaculture. Naturally occurring or wild organisms may also affect the well-being of cultured animals in various ways through predation and parasitism.

2.2 Effect of Aquaculture on the Environment

Aquaculture exerts a wide range and degree of impact on the surrounding environment. While traditional aquaculture was more environment friendly with low nutritional inputs, the increasing use of nutrient-dense pelleted feed in modern intensive aquaculture has led to major environmental concerns (Edwards 2015). Firstly, eutrophication of water and sediments from the discharge of farm effluents and waste output is a common impact associated with intensive aquaculture. Secondly, aquaculture can affect the biological diversity and community dynamics in the water bodies receiving the farm effluents. In the area adjacent to fish farms, accumulation of particulate nutrient wastes from uneaten feed and excreta in sediments could cause major changes in the structure and function of benthic ecosystems, i.e., decrease the diversity of the benthic fauna and flora. With the decomposition of accumulated organic matter through microbial processes, highly reduced conditions could form due to sulfide accumulation and oxygen-demanding microbial processes like nitrification are inhibited. Consequently, high ammonium and phosphate are released from fish farm sediments (Mente et al. 2006). In the water column, the assimilation capacity of suspended and dissolved nutrients is mediated by nutrient uptake by phytoplankton and further transfer to higher trophic levels and dilution of nutrients mediated by hydrodynamics at the fish production sites. Besides nutrient enrichment (nitrogen, phosphorus, and carbon) and changes in gaseous components (oxygen, ammonia, hydrogen sulfide, and methane), aquaculture is also criticized for physical damage and destruction of natural environments and alterations of water flow. For instance, widespread destruction of mangroves was done in the past for the construction of shrimp and fish ponds. With respect to biological effects, reduction of natural biodiversity, changes in wild fish population due to escapees, parasites, and pathogens, and attraction of wild biota to the culture area have been observed (Iwama 1991). Although there is no consensus or sufficient understanding on how to manage the impact of aquaculture on the natural environment, an emerging view is to apply the principle of “ecosystem-based approach to aquaculture.”

3 Nutrition and Waste Outputs in Aquaculture

The efficient conversion of feed into fish or shellfish biomass is the primary goal of any fed aquaculture practice; however, the generation of waste outputs are inherently associated with this process (Cho and Bureau 1997). Nutrition feeds and feeding practices are thus considered to be a vital cog in the bidirectional relationship between fish production systems and the aquatic environment. The net environmental nutrient loading (i.e., the nutrients lost from feed and fertilizers) varies depending on the production system, cultured species, and type of feed used. In the last decade itself, an annual environmental nutrient load of 1.7 million metric tonnes of nitrogen and 0.46 million metric tonnes of phosphorus could be attributed to the aquaculture production of finfish and crustaceans (Verdegem 2013). Concerning the management of waste outputs, aquaculture differs from terrestrial livestock farming due to the challenges in measuring actual feed intake, retrieving unconsumed feed, estimating waste outputs, monitoring the rapid dispersal of wastes into the surrounding water, and applying waste containment measures (Cho and Bureau 1997). As the sustainability of aquaculture operations depends on their ability to reduce waste outputs, it is imperative to tailor feeds according to the farming system, environment, and fish and use feeds optimally for achieving a feed efficiency of one or above (Kamalam et al. 2020).

3.1 Feed Mass Balance and Nutrient Loading

In fed aquaculture operations, a typical aquaculture nutrient mass balance includes feed input, uneaten feed, biomass gain, and fecal and non-fecal losses. Individual fish excrete dissolved inorganic nutrients (non-fecal wastes) as a function of nutrient metabolism and defecate particulate organic nutrients (solid waste) as a function of diet digestibility (Bureau and Hua 2010). Resuspension of the particulate fraction results in the remaining dissolved organic nutrients load. Unconsumed feed and larger fecal particles will sink, accumulate in sediments, and affect benthic communities, whereas the dissolved inorganic and organic nutrients may affect the pelagic communities and the quality of rearing water. Using nutrient mass balance methods and bioenergetic approaches, the waste output from aquaculture facilities can be estimated or predicted based on feed use, fish biomass, N and P content in feed and fish, and their digestibility/assimilation efficiencies. Nutrient loading in aquaculture is actually the difference between nutrients supplied through feed and nutrients harvested in the form of fish biomass, and it is a function of the production environment, species, and system design. For instance, the nutrient loading is negative for the production of mollusks, while there is net nutrient loading in the production of farmed fish and crustaceans. Similarly, the nutrient loading is high in freshwater aquaculture, when compared to brackish water and marine aquaculture (Dewey et al. 2011; Verdegem 2013). For salmonids, nutritional bioenergetics-based feeding guides are available for different water temperatures and high-energy diets. Even bioenergetic models and computational software such as the Fish-PrFEQ

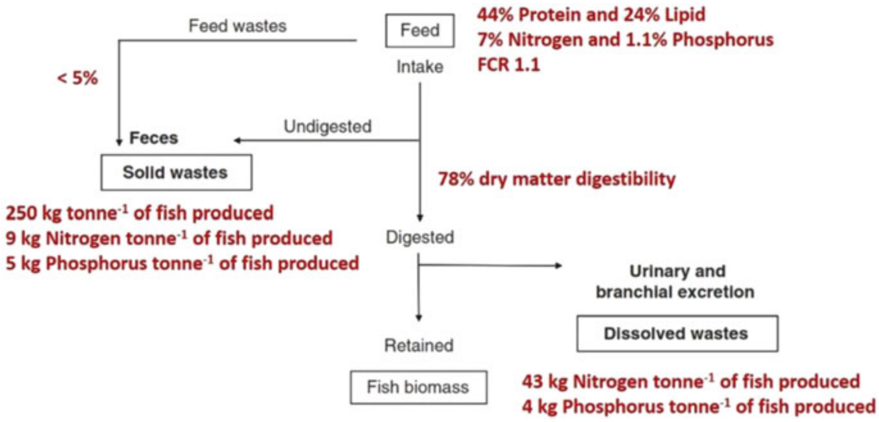

Fig. 2 Example of a nutrient partitioning and loading scheme in farmed rainbow trout. (Source: Bureau and Hua 2010)

program and FiShit have been developed to predict growth, apparent digestibility, nutrient (N and P) retention, and waste outputs (Cho and Bureau 1998; Fig. 2). Applying the same bioenergetic principles and advanced methodological tools, it is also possible to estimate waste output and nutrient loading for non-salmonid fish species (Kaushik 1998). For the environmental sustainability of aquaculture, more attention should be given to increasing the retention of dietary phosphorus (from the present 40% P retained), as excessive discharge of this rate-limiting nutrient leads to undesirable and harmful impacts on the freshwater ecosystems (Sugiura 2018).

3.2 Management of Waste Outputs

To ensure the sustainability of aquaculture, the first important step is to have an objective estimate of the amount of waste—nitrogen, phosphorus, and fecal solids associated with fish production and its environmental impact (Bureau and Hua 2010). Subsequently, the management and control of aquaculture waste output should begin with changes in diet formulation and feeding strategies, as feed is the primary source of waste and enriching nutrients (Cho and Bureau 2001). Low-pollution diets that are highly digestible could be an effective solution to reduce solid waste. Digestibility and nutrient availability (particularly for phosphorus) can be improved by choosing the right feed ingredients and processing methods. Nutrient utilization, retention, and loss are directly linked to the quality of the feed (Kong et al. 2020). Dietary manipulations aimed at increasing water stability and fecal consistency by fine-tuning feed formulations with suitable ingredients and additives could also improve solid removal efficiency from farm effluents. Optimizing protein and energy balance in the diet (by reducing digestible protein to digestible energy ratio) can help in improving N retention and reducing N wastes, as more non-protein dietary components are used as energy sources by the fish. Accurate estimations and information on P requirement of different life stages of fish, P bioavailability in feed ingredients, and formulation of feeds based on available P content help to reduce P levels in farm effluents. In addition to changes in feed formulation, following a proper feeding schedule (ration size, frequency, and meal timing) could help in minimizing the amount of uneaten feed and feed wastage. Likewise, strategies like phase feeding with different feeds during a particular period of production, i.e., low P diets during grow-out stages can significantly lower nutrient loss without compromising fish performance and profitability (Hardy and Gatlin 2002; Amirkolaie 2011). Through different nutritional strategies focused on minimizing the amount of uneaten feed and on enhancing the retention of N and P, a significant reduction in waste outputs has been already achieved per unit of fish produced in commercial aquaculture operations. For example, a highly digestible low-pollution feed with an efficiency of more than one is known to yield less than 150 kg solid waste output and 3 kg phosphorus per metric ton of salmonid fish produced (Cho and Bureau 1997).

In the last two decades, the production of dietary origin aquaculture waste has decreased substantially due to pivotal advances in feed manufacturing (extrusion) technology that yields less than 1% fine particles in the feed. Concurrent to this, the application of bioengineering and biotechnological strategies for improving the quality of conventional feed ingredients (e.g., fermented soy and soy protein concentrate) and for producing new feed ingredients (single-cell proteins) and major feed additives such as microbial phytases are vital for controlling the global environmental impact of aquaculture (Mayer and McLean 1995). More recently, the application of digital technologies and the use of smart feeding systems are transitioning feed management from an experience-driven to a knowledge-driven process. Through machine vision and learning algorithms, feeding behavior and excess feed can be monitored, profiled, and used to predict fish appetite and control feed delivery via automated systems (Gladju et al. 2022). The enforcement of environmental regulations and legislative measures for aquaculture operations started in Denmark (where the use of wet feed was forbidden in 1985) and has spread to all the other developed countries with strict limits for N, P and organic matter concentration in farm effluents and even in diet composition (Enell 1995; Iversen 1995). Such regulations to safeguard the environment must also be implemented in low- and middle-income countries.

4 Evolution of Fish Feed in the Environmental Context

Historically, environmental sustainability (minimizing pollution due to wet feeds) was one of the major factors that triggered the reorientation and development of dry feeds and the present-day feed industry (Hansen 2019). With further technological progress, dry feeds have led to optimal use of feed resources, minimum spoilage, and higher production yields in aquaculture. As the focus on environmental sustainability increases, there is a greater emphasis on the use of feed resources in a responsible and environmentally efficient manner. This includes enhanced traceability of aquaculture feed ingredients, limiting the inclusion of fish meal and fish oil sourced from overexploited wild fishes and the use of novel plant, animal, and micro-organism-based raw materials which have less ecological costs (Fig. 3). As the global feed industry aims to become more sustainable, there would be more interactions between external pressures, institutions, and technologies for further feed innovation and transformational development.

4.1 Fish Feed and Wild Fisheries

Conventionally, in commercial fish feeds, fish meal and fish oil were the major protein and lipid source as they are highly digestible, rich in vital nutrients (n-3 long-chain polyunsaturated fatty acids and trace elements), and closely reflect the natural diet of many farmed fish species. These ingredients are unsustainably rendered from 18 million tonnes of small marine pelagic fish such as anchovies, sardines, and herrings, although most of these are fit for human consumption (FAO 2020). With the rapid growth of the aquaculture sector, the increased demand for fish meal and fish oil has led to a spiraling increase in their prices and additional pressure on wild forage fish landings and marine ecosystems. According to a projection, by 2037, the demand for fish meal and fish oil in aquafeeds could outrun the supply of small forage fish (Naylor et al. 2021). Considering this, over the last three decades, significant progress has been made in reducing the levels of fish meal and fish oil in aquafeeds, with improved efficiency of their use. Along the aquaculture supply chain, the reduction in the use of marine ingredients has been reinforced by sustainability goals. Still, the share of fish meal and fish oil used by the aquaculture sector is 69% and 75%, respectively. To allow continuous growth, the aquaculture feed industry is progressively shifting to crop based and other terrestrial ingredients, linking fish and seafood production to terrestrial agriculture with a completely different set of environmental and planetary health implications (Fry et al. 2016).

4.2 Replacements for Marine Ingredients

In commercial aquafeeds, a large proportion of fish meal is presently replaced by plant-based ingredients (oil seeds, legumes, and grains), mainly soy and corn-based products such as soy protein concentrate and fermented soybean meal. The plant-based ingredients are selected based on reduced content of antinutritional factors and improved protein content and digestibility. They are widely available, relatively inexpensive, and can meet the nutritional requirements of farmed fish and crustaceans. Likewise, improved varieties of canola oil that are rich in n-3 long-chain polyunsaturated fatty acids (PUFA) have been developed with proven potential to replace fish oil in aquafeeds (Kamalam et al. 2020). Nevertheless, plant-based ingredients have also been scrutinized and criticized for their environmental impacts such as large-scale deforestation for soy farming (Fry et al. 2016). Higher inclusion of plant-based ingredients may also result in increased nutrient loss and waste

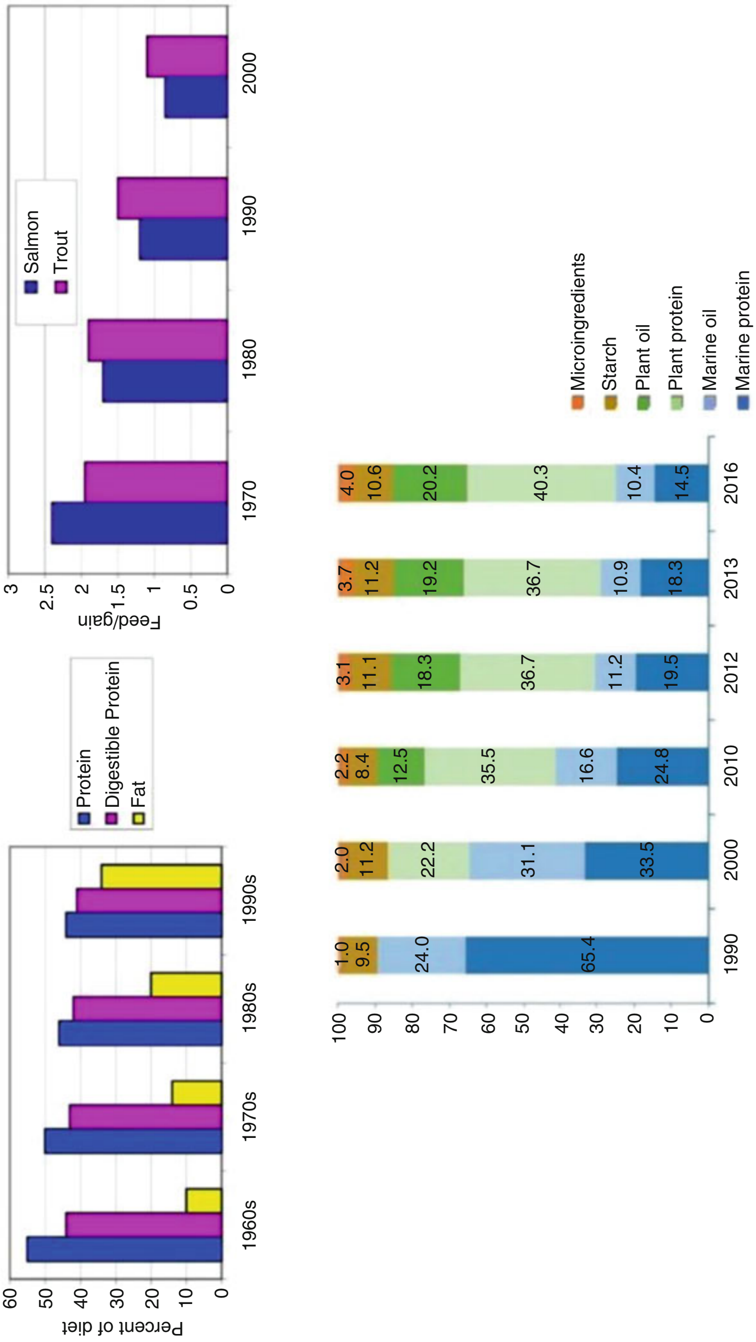

Fig. 3 Evolution of salmonid feeds over the years with respect to composition and feed efficiency (Source: Hardy and Gatlin 2002; Hansen 2019)

outputs due to long-term effects on the digestive system and associated gut microbes (Médale et al. 1998).

Microalgae is a more potential replacement for marine ingredients, as they naturally form the bottom of the aquatic food chain. They are an excellent source of amino acids and n-3 PUFAs, and their inclusion could be beneficial during the early and critical life stages of aquatic animals. It is also possible to produce and extract n-3 long-chain PUFAs rich algal oil by fermentation process (Veramaris omega-3 oil; https://www.veramaris.com/), creating a food chain shortcut that bypasses marine habitats. One tonne of this algal oil could effectively save sixty tonnes of wild-caught fish. The present cost of production of high-quality microalgae-based feed products is however a limitation for substantial incorporation in commercial feeds (they are presently used only as supplements), despite their positive effect on the growth and health of multiple fish species (Couture et al. 2019). Other sustainably produced feed ingredients include bacteria, yeast, other single-cell proteins, and insect meals. Particularly, several insect protein sources such as black soldier fly larvae, mealworm, and cricket meal have promising nutritional value coupled with economic feasibility to substitute fish meal in aquafeeds. With increasing demand, insect meal producers across the world are presently scaling up production to supply at a commercially sustainable rate (Kamalam et al. 2020). For the future of aquafeeds, there is an expanding list of sustainably produced alternative ingredients with high nutritional value. The increasing role of terrestrial food systems in aquaculture is governed by the development of feed ingredients tailored to the cultured species; formulations based on the precise estimation of nutritional requirements; and selective breeding of fish to efficiently grow on sustainable feeds (Naylor et al. 2021).

5 Environmental Footprint of Feed

Feed transition from marine ingredients to alternate resources is presently driven by bioeconomic policies without adequately assessing challenges related to environmental sustainability, protection, and climate change consequences (Hansen 2019). Conversely, life cycle assessments suggest that fish feed (as a crucial input factor) is responsible for more than 90% of the environmental impact of aquaculture production (Naylor et al. 2021). Life cycle analysis (LCA) is a technique that is used to assess the environmental aspects and impacts throughout the life of a product or service from raw material sourcing, processing, energy extraction, production, use of the product, and disposal, including transportation and packaging at all stages. For more reliable estimates of the environmental impact of aquaculture operations and aquafeed, the methodological issues in LCA related to the setting of system boundaries, assigning of functional units, multi-functionality of processes, coverage of environmental impacts, and critical interpretation need to be resolved. Emphasis should also be given to constructing a multiple-indicator aquaculture LCA inventory or global database covering all the relevant impacts of fish farming (Bohnes and Laurent 2019). This should be along the lines of the massive analysis of

Table 1 Environmental footprint of major animal food commodities (adapted from Poore and Nemecek 2018)

Commodity	Land use (m^2/kg)	Water use (L/kg)	Eutrophy emmision (g PO_4 eq./kg)	GHG emission (kg CO_2 eq./kg)
Fish (farmed)	8.4	3691	235.1	13.6
Shrimp (farmed)	2.97	3515	227.2	26.9
Beef	326.2	1451	301.4	99.5
Lamb and mutton	369.8	1803	97.1	39.7
Pig meat	17.4	1796	76.4	12.3
Poultry meat	12.2	660	48.7	9.9
Eggs	6.3	578	21.8	4.7
Milk	8.95	628	10.7	3.2

heterogenous and inherently variable food systems that have been carried out using different environmental indicators to develop an integrated mitigation framework (Poore and Nemecek 2018; Table 1). Mitigation strategies are complicated by variable and skewed environmental impacts, trade-offs, supply-chain interactions, and multiple practices.

5.1 Life Cycle Assessment of Salmonid and Carp Feeds

To understand the environmental burdens associated with the production of aquafeeds and to improve the environmental performance of aquaculture operations, environmental impact assessments of aquafeeds are increasingly carried out covering their water and land requirement for producing ingredients, energy usage, greenhouse gas emission, and eutrophication potential. In one of the first LCA study of the environmental impacts associated with aquafeed, four rainbow trout feeds used in France were investigated (Papatryphon et al. 2004). The stages assessed were raw material extraction, production, and transformation of primary ingredients, feed manufacturing, feed use at the farm, transport at all stages, and production/use of energy sources. The results suggested that the use of marine ingredients and farm nutrient emissions contributes most to the environmental burden of trout feeds. Conversely, good management practices, quality plant-based ingredients, and fish meals that are a by-product of processing can improve the environmental profile of the feed (Fig. 4).

Similarly, an environmental assessment of fish meal substitution in feeds of Indian major carps under polyculture was carried out using attributional LCA (Aubin et al. unpublished). This first-ever application of LCA methodology in the Indian aquaculture system showed the balanced advantage of decreasing the use of marine protein sources (fish meal) in aquafeeds and also the impact of using

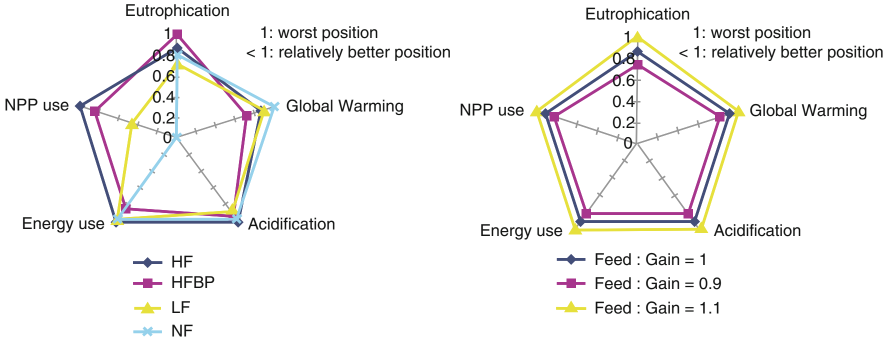

Fig. 4 Radar charts comparing the environmental impact of rainbow trout feed with different fish meal content and FCR. (Source: Papatryphon et al. 2004)

plant-origin ingredients. It offers a perspective of the combined nutritional and environmental optimization of aquafeeds. Conventionally, in carp polyculture ponds that receive supplementary feeds and fertilizers for natural food production, environmental nutrient loading from manure (75–95% of N-input and 89–95% of P-input) can be more than from feed (47–79% of N-input and 72–89% of P-input; Iwama 1991). Therefore, more use of low-pollution formulated feeds, feeding niche management, and adoption of environmentally compatible feeding strategies may help to reduce the environmental footprint of carp polyculture (Tacon et al. 1995; Saravanan et al. 2012).

5.2 Life Cycle Assessment of Novel Feed Ingredients

The full-scale shift towards insect meals, microalgal products, and single-cell proteins (bacteria and yeast) should be accompanied by environmental impact assessments regarding potential conflicts in the use and production of these resources and cross-system effects on neighboring ecosystems (Hansen 2019). In this direction, an attributional life cycle assessment was conducted to comparatively evaluate the environmental impact of salmon feeds industrially prepared from soy protein, yeast protein, and methanotrophic bacterial meal, using seven emission and resource use indicators (Couture et al. 2019). Compared to soy protein concentrate, yeast protein concentrate showed drastically lower environmental impacts in all categories such as climate change, eutrophication, land and water use, acidification, and primary production requirements. Except for water use and climate change, the methanotrophic bacterial meal also showed lower impacts than soy protein for all the other environmental indicators. The results indicate that the use of single-cell proteins from yeast and bacteria in salmon feed can greatly improve the environmental performance of salmon production (Fig. 5). The development of new feed resources for aquaculture should be done in an environmentally sustainable manner, without straining the already limiting or unsustainable resources.

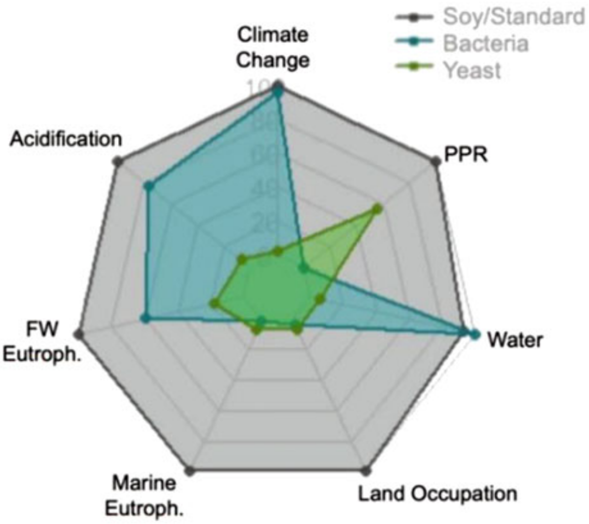

Fig. 5 Radar charts comparing the environmental impacts of soy, bacteria, and yeast meals. (Source: Couture et al. 2019)

6 Environmental Influence on Feed Utilization

While the regulatory role of aquaculture feeds in deciding the environmental impact and sustainability of aquaculture systems is well recognized, the impact of environmental changes on the nutritional requirements of fish and the biological efficiency of feed compositions are less understood, but gradually gaining attention. Changes in the aquatic environment would affect the multiple sensory systems (vision, olfaction, and taste), feeding behavior, and feed utilization in fish. Also, changes in environmental factors are known to influence the energy and nutritional requirements of fish, especially that of minerals (Kamalam et al. 2020). With respect to digestibility and retention of nutrients, a decrease in temperature leads to decreased dry matter and protein digestibility in rainbow trout, resulting in higher fecal solids and nitrogenous waste outputs per kilogram of fish produced (Azevedo et al. 1998). On the contrary, with increasing water temperature, the metabolic rate of salmonids increases and they are more likely to experience hypoxic conditions. Such limiting environmental conditions challenge the respiratory physiology and adequacy of nutrient supply for fish growth. Even with the progressive shifts in feed formulation, there is less information on the changes in nutritional requirements of fish and their response to low fish meal/oil feed compositions, under varying environmental conditions. Inadequate nutrition may aggravate the stress under sub-optimal culture conditions and may lead to impaired physiological homeostasis.

7 Nutritional Intervention to Mitigate Environmental Stressors

Dietary interventions (functional feeds) are a practically feasible strategy for environmental stress management in aquaculture. For instance, in salmon farming, extra provision of n-3 long-chain polyunsaturated fatty acids is known to improve fish health and performance under challenging environmental conditions. Similarly, dietary fortification with natural antioxidants (vitamin C and E), amino acids (tryptophan, arginine, and pyridoxine), phospholipids, trace elements (selenium, iron, and zinc), and probiotics have been reported to ameliorate environmental stressors in fish (Kamalam et al. 2020). Nevertheless, it should be noted that supplement dosage can be specific to species, life stages, and cultural environment. There is a robust body of evidence to suggest that nutraceuticals and dietary supplements can modulate the immune system, antioxidant status, and intermediary metabolic pathways to confer a beneficial effect on the well-being and stress tolerance of fish, under adverse environmental conditions (Ciji and Akhtar 2021).

8 Conclusion

Over the last two decades, the aquaculture industry has faced immense pressure to adopt wide-ranging sustainability measures, which have eventually improved the technology, management, and governance in global fish farming systems. There is no apparent quick fix or panacea for environmentally sustainable aquaculture, as it expands to meet the ever-increasing demand for fish and seafood. Environmental performance efficiency of aquaculture operations has to be achieved through proper site selection, efficient use of water and land resources, integration of traditional and modern culture practices, effective waste management, and adoption of best aquaculture practices. Importantly, innovations in feed, ingredients, and improved feed efficiency is a pre-requisite to making aquaculture environmentally sustainable. At reduced inclusion levels, the importance of fish meal and fish oil will remain as a specialty ingredient that supplies highly essential nutrients to support growth, survival, development, maturation, and reproduction at critical life stages. Integrated resource management (water, land, nutrients, biota, labor, and capital) may support the optimal use of all resources and thereby increase the environmental and socioeconomic sustainability of aquaculture farms. The aquaculture industry should be prepared to reconfigure and respond to newer sustainability concerns over time, as technologies and transitions are not sustainable in themselves. Countries must develop their legislation and regulations concerning feed, feeding, and the environment.

References

Amirkolaie AK (2011) Reduction in the environmental impact of waste discharged by fish farms through feed and feeding. Rev Aquac 3(1):19–26

Azevedo PA, Cho CY, Leeson S, Bureau DP (1998) Effects of feeding level and water temperature on growth, nutrient and energy utilization and waste outputs of rainbow trout (*Oncorhynchus mykiss*). Aquat Living Resour 11(4):227–238

Bohnes FA, Laurent A (2019) LCA of aquaculture systems: methodological issues and potential improvements. Int J Life Cycle Assess 24(2):324–337

Bureau DP, Hua K (2010) Towards effective nutritional management of waste outputs in aquaculture, with particular reference to salmonid aquaculture operations. Aquacult Res 41(5):777–792

Cho CY, Bureau DP (1997) Reduction of waste output from salmonid aquaculture through feeds and feeding. Progr Fish Cult 59(2):155–160

Cho CY, Bureau DP (1998) Development of bioenergetic models and the fish-PrFEQ software to estimate production, feeding ration and waste output in aquaculture. Aquat Living Resour 11(4): 199–210

Cho CY, Bureau DP (2001) A review of diet formulation strategies and feeding systems to reduce excretory and feed wastes in aquaculture. Aquacult Res 32:349–360

Ciji A, Akhtar MS (2021) Stress management in aquaculture: a review of dietary interventions. Rev Aquac 13(4):2190–2247

Couture JL, Geyer R, Hansen JØ, Kuczenski B, Øverland M, Palazzo J, Sahlmann C, Lenihan H (2019) Environmental benefits of novel nonhuman food inputs to salmon feeds. Environ Sci Technol 53(4):1967–1975

Dewey W, Davis JP, Cheney DC (2011) Shellfish aquaculture and the environment: an industry perspective. In: Shellfish aquaculture and the environment, pp 33–50

Edwards P (2015) Aquaculture environment interactions: past, present and likely future trends. Aquaculture 447:2–14

Enell M (1995) Environmental impact of nutrients from Nordic fish farming. Water Sci Technol 31(10):61–71

FAO (2020) The state of world fisheries and aquaculture 2020. Sustainability in action, FAO, Rome. https://doi.org/10.4060/ca9229en

Fry JP, Love DC, MacDonald GK, West PC, Engstrom PM, Nachman KE, Lawrence RS (2016) Environmental health impacts of feeding crops to farmed fish. Environ Int 91:201–214

Gladju J, Kamalam BS, Kanagaraj A (2022) Applications of data mining and machine learning framework in aquaculture and fisheries: a review. Smart Agricult Technol 2:100061. https://doi.org/10.1016/j.atech.2022.100061

Hansen L (2019) The weak sustainability of the salmon feed transition in Norway—a bioeconomic case study. Front Mar Sci 6:764

Hardy RW, Gatlin DM III (2002) Nutritional strategies to reduce nutrient losses in intensive aquaculture. In: Cruz-Suárez LE, Ricque-Marie D, Tapia-Salazar M, Gaxiola-Cortés MG, Simoes N (eds) Avances en Nutrición Acuícola VI. Memorias del VI Simposium Internacional de Nutrición Acuícola. 3 al 6 de Septiembre del 2002. Cancún, Quintana Roo, México

Iversen TM (1995) Fish farming in Denmark: environmental impact of regulative legislation. Water Sci Technol 31(10):73–84

Iwama GK (1991) Interactions between aquaculture and the environment. Crit Rev Environ Sci Technol 21(2):177–216

Kamalam BS, Rajesh M, Kaushik S (2020) Nutrition and feeding of rainbow trout (*Oncorhynchus mykiss*). In: Ninawe AS, Dhanze JR, Dhanze R, Indulkar ST (eds) Fish nutrition and its relevance to human health. CRC, Taylor and Francis, Boca Raton, FL, pp 299–332. https://doi.org/10.1201/9781003107583

Kaushik SJ (1998) Nutritional bioenergetics and estimation of waste production in non-salmonids. Aquat Living Resour 11(4):211–217

Kong W, Huang S, Yang Z, Shi F, Feng Y, Khatoon Z (2020) Fish feed quality is a key factor in impacting aquaculture water environment: evidence from incubator experiments. Sci Rep 10(1): 1–15

Mayer I, McLean E (1995) Bioengineering and biotechnological strategies for reduced waste aquaculture. Water Sci Technol 31(10):85–102

Médale F, Boujard T, Vallée F, Blanc D, Mambrini M, Roem A, Kaushik SJ (1998) Voluntary feed intake, nitrogen and phosphorus losses in rainbow trout (*Oncorhynchus mykiss*) fed increasing dietary levels of soy protein concentrate. Aquat Living Resour 11(4):239–246

Mente E, Pierce GJ, Santos MB, Neofitou C (2006) Effect of feed and feeding in the culture of salmonids on the marine aquatic environment: a synthesis for European aquaculture. Aquac Int 14(5):499–522

Naylor RL, Hardy RW, Buschmann AH, Bush SR, Cao L, Klinger DH, Troell M et al (2021) A 20-year retrospective review of global aquaculture. Nature 591(7851):551–563

Papatryphon E, Petit J, Kaushik SJ, van der Werf HM (2004) Environmental impact assessment of salmonid feeds using life cycle assessment (LCA). Ambio 33(6):316–323

Poore J, Nemecek T (2018) Reducing food's environmental impacts through producers and consumers. Science 360(6392):987–992

Saravanan K, Prabhu AJ, P and Kamalam, B. S. (2012) Feeding strategies adopted by fish farmers in Andhra Pradesh, India. Aquacult Asia 17(1):21–24

Sugiura SH (2018) Phosphorus, aquaculture, and the environment. Rev Fish Sci Aquacult 26(4): 515–521

Tacon AGJ, Phillips MJ, Barg UC (1995) Aquaculture feeds and the environment: the Asian experience. Water Sci Technol 31(10):41–59

Verdegem MC (2013) Nutrient discharge from aquaculture operations in function of system design and production environment. Rev Aquac 5(3):158–171

Reproductive and Maternal Nutrition in Changing Climatic Conditions

Zsuzsanna J. Sandor

Abstract

Temperature is a fundamental physical regulatory factor in the lives of fishes and this effect is expressed particularly strong in the control of all reproductive stages viz. gametogenesis and gamete maturation, ovulation/spermiation, spawning and early developmental stages and survival. An improvement in broodstock nutrition and feeding greatly improved not only egg and milt quality but also seed production. Thus, more attention has been paid to the level of different nutrients in broodstock diets under the changing climate condition. The fact that for the success of reproduction and finally to the vitality of progeny, maternal nutrition with well-balanced nutrients has high priority.

Keywords

Climate change · Broodstock · Reproduction · Feed

1 Introduction

Changes in the physical and chemical properties of aquatic ecosystems inevitably have an impact on the physiology of most organisms. Changes in environmental temperatures are the most important environmental factor affecting fish physiology, however other parameters are also important like photoperiod, ocean acidification, and salt concentration. Besides the expected effect of changing the environmental

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conditions on the growth and health of the fish, modulation in sexual reproduction is inescapable.

Climate change affects not only the reproduction physiology, thus to the safety of production and quality of the feeds. The requirement for high protein and fat levels in the diets of broodstock predicts the need for proper nutritional management in aquaculture systems. Demand for new and sustainable ingredients will occur. High temperature and increased humidity in the summer period would have an impact on boosting the mold development in the cereals/grains or on the surface of feeds. The occurrence of mycotoxin in the feeds for breeders is as dangerous as for juvenile fish.

From the possible consequences of proper maturation and spawning of fish, this section covers only the problem with the nutrition of the breeders in aquaculture systems, the sustainable feed ingredients, the digestibility of the diet, and finally the toxicology of relevant toxins observed in the feeds which may endangers reproduction success.

2 Nutritional Requirement of Brooders. Impact of the Climate on Feed Utilization)

Oocyte maturation is one of the energy-consuming metabolic activities in fish, and the quality of the broodstock diet is the primary aspect of providing bioavailable nutrients to the oocytes and success in their maturation (McBride et al. 2015; Volkoff and London 2018). It was demonstrated that improper nutrition can result in a negative impact on oocyte development (Rainuzzo et al. 1997). The protein requirement of the brooders of most of the fish did not determine experimentally, however, it is considered that the protein requirement of brood fish is higher than their growing phase and similarly high as for the juvenile stage. The requirement of fish decreases with age, but in the maturation stage, the need for protein increases. The protein levels in the aquafeeds of breeders are generally from 40% up to 55% crude protein (CP); therefore, the protein level is set between 23% and 55% for juveniles and grower stage (Molina-Poveda, 2016 in Aquafeed formulation edited by Nates). More focus is given to essential amino acid requirements and has been established for several aquaculture important species. The supplementation with crystalline amino acids in the diets is practiced today to meet the EAA requirement. Methionine and lysine are the main limiting AA when using high levels of plant ingredients in diets.

The lipid in the broodstock diet is essential for better reproductive performance and also determines the gamete quality, fecundity, fertilization, and also survival of fish larvae (Izquierdo et al. 2001). The fatty acid profile and the PUFA content of the diet are also important factors that play a vital role during the maturation of oocytes. Some fishes readily incorporate dietary lipids in the yolk during the spawning season. However, n-6 and n-3 PUFAs have to be supplied in the diet of fish, either as arachidonic acid (AA 20:4n-6), eicosapentaenoic acid (EPA, 20:5n-3), or docosahexaenoic acid (DHA 22:6n-3) or as their precursors, such as linoleic acid

(LA, 18:2n-6, precursor of AA) and a-linolenic acid (LNA, 18:3n-3, precursor of EPA and DHA) since they cannot be synthesized in vivo by most metazoans.

The requirement of Lc-PUFA or total n-3 FA has been investigated for several fish species such as turbot (Lavens et al. 1999), red sea bream (Watanabe et al. 1984), gilthead sea bream (Rodriguez et al. 1998), Japanese flounder (Furuita et al. 2002), seabass (Bell et al. 1997), rainbow trout (Vassallo-Agius et al. 2001), tongue sole (Liang et al. 2013), Penaeus monodon (*Fabricius*) (Meunpol et al. 2005), pike perch and Eurasian perch (Kestemont and Henrotte 2015), common carp var. koi (Harshavardhan et al. 2021), and common carp (Xu et al. 2017). These studies revealed that an inappropriate LcPUFA ratio could impair reproduction performance. A proper balance of both n-6 and n-3 PUFAs is necessary for a broodstock diet for the optimum reproductive success of fish. However, the requirement of PUFAs varies from fish species to fish species.

The nutrient utilization is strongly related to the digestibility of each nutrient which depends on the available enzymes in the stomach or intestine of the fish. The digestive enzymes' activities are affected by the living water temperature of the fish and could be defined as an optimum value for it. To optimize feed intake and feed efficiency of the cultured species monitoring of water quality conditions, including water temperature, dissolved oxygen levels, feeding frequency, feeding method, etc. is needed to follow internationally recognized good or best on-farm feed management practices. Mitigation of a certain increase in water temperature by covering the ponds has success in today's practice.

3 Sustainably Feeds and Ingredients for Brooders: Challenges and Obstacles in Feed Availability in Changing Climate Conditions

Sustainable aquaculture needs sustainable feed ingredients for continuous and safe aquaculture production. Parallel to fishmeal demand for aquafeed production its price has been raised very intensively in the last decades. The industrial production of fishmeal is based on the availability of certain wild-caught, fast-growing, short-lived pelagic fish, which are predominant in subtropical and temperate regions The extreme weather conditions and sea-level rise would also harm coastal eco-system and their communities. All these impacts associated with climate change at long last diminish the wild stock of pelagic fish (Jannathulla et al. 2019). Global warming would result in poleward mowing (fish move from warmer water to colder) resulting in differentiation in fish yield, as a consequence, north countries would have a significantly high yield compared to the south part of the globe.

The availability of terrestrial plant ingredients is deeply influenced by increased temperature caused by climate change. The feed factories started to increase flexibility with raw materials enabling available materials from renewable biological resources from land and sea, such as crops, forests, agriculture, and industrial by-product, from the processing of fish and land animals, microorganisms, and other materials like brewer's yeast. These ingredients would otherwise be wasted if not used in aquafeed production. Moreover, the feed industry is using increasing volumes of ingredients that do not compete with human consumption, such as insect meals, protein from single-cell organisms, and cultured algal products. The use of these ingredients represents an efficient use of natural resources and supports the development of a circular economy. Current global feed ingredient usage is comprised of a significant amount of by-products and the industry actively searching for ingredients that will result in more innovative, low-emission aquaculture feeds. Diversification of marine raw materials is more and more important. In the last five years increased use of fish trimmings already decreased the forage fish dependency ratio. There is a goal to source only from sustainably managed fisheries. Is a strong need for raw materials with a lower footprint that is commercially and nutritionally relevant. 30% of the world's fishmeal production and 51% of fish oil production come from by-products (IFFO 2021 DATA). Generally, it is needed to reduce the carbon footprint of aquafeeds through the reduced use of imported feed ingredient sources and the increased use and recycling of locally available agricultural and fishery resources derived from sustainably managed and operated agricultural and fishery operations.

Climate change will have a higher impact on the feed industry in third-world countries facing the lack of crops or missing the new type of protein or oil coming from biotechnology investments. In this sense, there is a danger to producing feeds with unwell-balanced nutrients for maternal nutrition. Even more, the vulnerability of marine species to climate change and overfishing varies greatly, and micronutrient availability for animal and human nutrition would be critical in the same countries. It is required to identify countries where interventions can optimize micronutrient supply and also the analysis highlights the need to consolidate fisheries, climate, and food policies to secure the sustainable contribution of fish-derived micronutrients to food and nutrition security (Maire et al. 2021).

On the other side increased temperature will have a strong effect on the quality and safety of the feeds in this region. The air humidity contributes to the development and growth of different fungi and in positive conditions may favor the synthesis of mycotoxins. Losses in aquaculture caused by mycotoxins in feed would be significant and negatively influence production. The toxic effect of mycotoxins certainly depends on the type and quantity of mycotoxin content in the feed, but also depends on the duration of exposure, animal species, sex, and age. The most relevant effect determined in fish is carcinogenicity of the liver, damage to cell kidney, and genotoxicity. Then, can cause suppression of the immune system or estrogenic syndrome, induce cell and organ alterations and lead to mortality (Anater et al., 2016). To protect the feeds in aquaculture practice, it is required for farmers to store their feeds under cool and well-ventilated conditions to maintain the quality and nutrient stability of the feeds.

4 Effect of Climate Condition on Reproduction

Temperature impact during gametogenesis itself (on the rate of development, recruitment, and gamete quality) is far clearer, as it impacts directly on the metabolic pathways in the brain–pituitary–gonadal (BPG) axis (Migaud et al. 2013). Thermal history can have a significant impact on the timing of ovulation. In general, cooler temperatures will delay development, while higher temperatures will advance it. This means that non-optimal temperatures due to climate change determine the future of the next fish population in the given region. Freshwater fishes are especially vulnerable to environmental changes associated with climate change because they are ectothermic; their migration among water bodies is constrained by terrestrial and physical barriers. In the ocean, fish may be experienced in selecting their habitats in which temperatures are favorable to growth or even dough to spawn because behaviourally fishes are thermoregulators. For example, common carp is reliant more on temperature than photoperiod to cue the reproductive cycle. In the wild, this determines the specific location in which spawning will occur, while in captivity this means that rearing temperature has to be strictly managed to achieve optimal egg quality and subsequent juvenile production (Servili et al. 2020).

When migration is restricted, the response of fish to environmental changes likely is through the generation and genetic adaptation (Schade et al. 2014). Relatively little is known about the capacity for plasticity of reproductive processes to change environments over multiple generations (transgenerational plasticity). The large majority of studies focused so far exclusively on the acclimation ability (phenotypic plasticity) of a fish species to one or a combination of changing environmental factors. Although understanding the transgenerational plasticity of fish species to the different climate change-related factors (warming, water acidification, hypoxia, and low salinity) is essential to be able to predict the real impact of climate change on fish populations. Since transgenerational plasticity is a fast and often adaptive phenotypic response mechanism, it can buffer populations against environments experienced by the previous generations and provide time for genetic adaptation to catch up (Bonduriansky et al. 2012).

Due to the increased temperature release, mobilization and transportation of the pollutants may occur in the aquatic environment. There are several climatic change stressors which had shown a positive correlation with the appearance of pollutants in a certain environment, for example, increasing the toxicity of heavy metals or herbicides with increased temperature (Kibria et al. 2021). The interactive effect of stressors (temperature and pollutants) can impact the aquatic biota through increasing toxicity, affecting growth and reproduction, and increasing bioaccumulation. It was found that the estrogenic chemicals (estradiol, ethinylestradiol, bisphenol-A) increased the vitellogenin (egg yolk precursor protein) level at higher temperatures (Brian et al. 2008), this implies that global warming may enhance vitellogenin on aquatic biota including fish.

Among the different mycotoxins, aflatoxins have the highest acute and chronic toxicity, including genotoxicity, carcinogenicity, and immunotoxicity. Zearalenone (ZEN) is a mycotoxin that is well known to cause reproductive problems in farm animals due to its estrogenic activity (Jia et al. 2016). ZEN belongs to a class of resorcylic acid lactones that bind to the estrogen receptor despite their non-steroidal structure (Arukwe et al. 1999). Another mycotoxin, alternariol (ALH) found in oily seeds has a weak estrogenic activity but an increased level of this ingredient in novel aquafeed may lead to a potential risk to the health of fish (Frizzell et al. 2013).

Although experimental data on toxicological aspects of ZEN action in fish models are constantly increasing, the influence of ZEN and other Fusarium mycotoxins on the growth and reproduction of economically important fish species has been incompletely evaluated. Furthermore, little is known about the ecotoxicological impact of ZEN (and its metabolites) as an environmental estrogen at levels found in surface waters and the consequence of exposure to aquatic organisms.

Exposure of fish to estrogens results in the induction of the yolk precursor protein vitellogenin in male and juvenile fish. ZEN is considered an endocrine active substance that exerts its effects by mimicking or antagonizing endogenous hormones, influencing the natural hormone synthesis, metabolism, or elimination and therefore has the potential to interfere with reproduction and development (Woźny et al. 2017). For example, water-borne exposure of zebrafish (*Danio rerio*) to ZEN can reduce spawning frequency (Schwartz et al. 2010) or induce transgenerational changes in fecundity (Schwartz et al. 2011). Effects of ZEN have been assessed in rainbow trout through short feeding and all life cycle feeding assays (Table 1.). These show that ZEN had a limited influence on the liver structure of the exposed fish in the short trial, although the results suggest that ZEN in the feed may accelerate the sexual maturation of the female fish (Woźny et al. 2015). Nevertheless, the results on the bioaccumulation of ZEN into muscle or ovary confirm that ZEN is transferred from the alimentary tract to the reproductive system of the fish, but remained non-detectable in the muscle (Woźny et al. 2015) (Table 2). The fish exposed to ZEN during life cycle feeding had morphological abnormalities in their gonads, and intersex fish and sex-reversed (feminized) males were found (Woźny et al. 2020). Although the ZEN exposure probably did not affect the timing of females' sexual maturation and their relative fecundity, it might have caused advanced ovarian development. ZEN exposure did lead to increased sperm concentration, as well as markedly elevated plasma concentrations of vitellogenin. The pharmacokinetic study (Woźny et al. 2017) confirms that ZEN is concentrated in the somatic cells of the ovaries, but is transferred to the oocytes and muscles only to a limited extent. These findings suggest that the presence of ZEN in the fish feed may have consequences for aquaculture and warrant the need for further research to reassess the recommended limits.

5 Dietary Manipulation to Mitigate Extreme Warm Stress in Fish: Role of Some Feed Additives

During extreme summer several strategies can be used to ameliorate negative effects on fish such as pond coverings, increasing depth, use of alternative culture techniques, and shifting of culture site and period. In addition, nutritional

Table 1 Toxic effects of zearalenone in fish after exposure

Species	Dose and exposure time	Administration	Toxic effect	References
Zebra danio	0.1–3.2 μg L^{-1} During 21 days	Water	Reduced spawning frequency and fecundity	Schwartz et al. (2010)
Zebra danio	0.32 and 1.0 μg L^{-1} 182 days (life cycle)	Water	Sex ratio was shifted toward female 1.5-fold induction of plasma vitellogenin in female	Schwartz et al. (2011)
Rainbow trout	1.8 mg kg^{-1} during 71 days	Oral	Structural irregularities of liver, including necrotic areas, disorders of polygonal hepatocytes, cytoplasm vacuolization, and macrophage aggregates No change in vitellogenin level	
Rainbow trout	2 mg kg^{-1} during 96 weeks (life cycle)	Oral	Morphological abnormalities in gonads Intersex fish—Feminized males Increased sperm concentration and vitellogenin concentration in plasma Parental exposure to ZEN in feed increased offspring mortality	

Table 2 Presence of zearalenone residues in fish organs

Species	Dose/administration period	Concentration	Tissue	References
Rainbow trout	Natural occurrence	7 ± 3 μg kg^{-1}	Ovary	Woźny et al. (2013)
Rainbow trout	1.8 mg kg^{-1} During 71 days	73.2 μg kg^{-1} ~40 μg kg^{-1} LOD, <5.0 μg kg^{-1}	Intestine Liver Muscle and ovary	
Rainbow trout	1 mg kg^{-1} Once oral tubing for pharmacokinetic study	350 μg kg^{-1} at 48 h, 70 μg kg^{-1} after 50 μg kg^{-1} at 12 h after administration, <LOD after	Ovary Muscle	

management strategies and adding functional ingredients to diets could be promising and helpful to manage temperature stress in aquaculture fish. Dietary manipulations through the addition of vitamins, photogenic, and beehive extracts have been employed for animals to boost their physiological capacity to counter inflammation and damage during stress exposure (Abdelnour et al. 2020; de la Cruz-Cervantes et al. 2018; Herrera et al. 2019). It is known that temperature stress provokes cellular oxidative stress, metabolic impairment, and immune dysfunction in fish (Islam et al. 2022). Therefore, antioxidants and non-specific immunostimulants such as vitamin C, E, propolis, phycocyanin, astaxanthin, and β-glucan can be used to ameliorate temperature stress in fish (Cheng et al. 2018). These functional additives offer animals better growth, physiological performance, antioxidants, and immune support. Simultaneously utilization of vitamins, propolis, and β-glucan as dietary additives decreased most of the stress parameters in European seabass (*Dicentrarchus labrax*) (Islam et al. 2021). In most of the performed studies, the targeted age of fish is the juvenile stage, but the same outcome could be prefaced when adult fish are fed using similar feed additives. However, dietary and nutritional manipulation's effectiveness depends first of all on species and concentration of bioactive compounds, similarly on duration and mode of administration. However, these topics are poorly studied and are required species and age-specific studies using stress-specific ingredients to maximize the benefits and avoid suppressive impacts.

Besides, dietary and nutritional management strategies could be another promising option to ameliorate thermal stress in fish. For example, the synthetic luteinizing hormone-releasing hormone has been found to improve reproductive performance and mitigate the inhibitory effects of elevated temperature in both sexes of *Salmo salar* (King and Pankhurst 2004), *O. niloticus* (Dussenne et al. 2020), and freshwater eels, Anguilla spp. (Burgerhout et al. 2019). A recent study by Fei et al. (2020) reported that dietary amino acids could enhance sex steroid hormone synthesis and growth performance of yellow catfish (*Pelteobagrus fulvidraco*). Dietary manipulation also improved the physiology of several fish species; however, the use of endocrine therapy and a nutritional management approach as potential thermal mitigation measures to support natural gametogenesis is still unexplored (Islam et al. 2021).

References

Abdelnour SA, Swelum AA, Salama A, Al-Ghadi MQ, Qattan SYA, Abd El-Hack ME, Khafaga AF, Alhimaidi AR, Almutairi BO, Ammari AA, El-Saadony MT (2020) The beneficial impacts of dietary phycocyanin supplementation on growing rabbits under high ambient temperature. Ital J Anim Sci 19:1046–1056. https://doi.org/10.1080/1828051X.2020.1815598

Anater A, Manyes L, Meca G, Ferrer E, Luciano FB, Pimpão CT, Font G (2016) Mycotoxins and their consequences in aquaculture: a review. Aquaculture 451:1–10. https://doi.org/10.1016/j.aquaculture.2015.08.022

Arukwe A, Grotmol T, Haugen TB, Knudsen FR, Goksøyr A (1999) Fish model for assessing the in vivo estrogenic potency of the mycotoxin zearalenone and its metabolites. Sci Total Environ 236:153–161. https://doi.org/10.1016/S0048-9697(99)00275-2

Bell JG, Farndale BM, Bruce MP, Navas JM, Carillo M (1997) Effects of broodstock dietary lipid on fatty acid compositions of eggs from sea bass (Dicentrarchus labtax). Aquaculture 149:107–119. https://doi.org/10.1016/S0044-8486(96)01436-6

Bonduriansky R, Crean AJ, Day T (2012) The implications of nongenetic inheritance for evolution in changing environments. Evol Appl 5:192–201. https://doi.org/10.1111/j.1752-4571.2011.00213.X

Brian JV, Harris CA, Runnalls TJ, Fantinati A, Pojana G, Marcomini A, Booy P, Lamoree M, Kortenkamp A, Sumpter JP (2008) Evidence of temperature-dependent effects on the estrogenic response of fish: implications with regard to climate change. Sci Total Environ 397:72–81. https://doi.org/10.1016/j.scitotenv.2008.02.036

Burgerhout E, Lokman PM, van den Thillart GEEJM, Dirks RP (2019) The time-keeping hormone melatonin: a possible key cue for puberty in freshwater eels (Anguilla spp.). Rev Fish Biol Fish 29(1):1–21. https://doi.org/10.1007/s11160-018-9540-3

Cheng CH, Guo ZX, Ye CX, Wang AL (2018) Effect of dietary astaxanthin on the growth performance, non- specific immunity, and antioxidant capacity of pufferfish (*Takifugu obscurus*) under high temperature stress. Fish Physiol Biochem 44(1):209–218. https://doi.org/10.1007/s10695-017-0425-5

de la Cruz-Cervantes JA, Benavides-Gonzalez F, Sanchez-Martínez JG, Vazquez-Sauceda ML, Ruiz-Uribe AJ (2018) Propolis in aquaculture: a review of its potential. Rev Fish Sci Aquac 26: 337–349. https://doi.org/10.1080/23308249.2018.1424798

Dussenne M, Gennotte V, Rougeot C, Mélard C, Cornil CA (2020) Consequences of temperature-induced sex reversal on hormones and brain in Nile tilapia (Oreochromis niloticus). Horm Behav 121:104728. https://doi.org/10.1016/j.yhbeh.2020.104728

Fei S, Liu C, Xia Y, Liu H, Han D, Jin J, Yang Y, Zhu X, Xie S (2020) The effects of dietary linolenic acid to linoleic acid ratio on growth performance, tissues fatty acid profile and sex steroid hormone synthesis of yellow catfish Pelteobagrus fulvidraco. Aquac Rep 17:100361. https://doi.org/10.1016/j.aqrep.2020.100361

Frizzell C, Ndossi D, Kalayou S, Eriksen GS, Verhaegen S, Sørlie M, Elliott CT, Ropstad E, Connolly L (2013) An in vitro investigation of endocrine disrupting effects of the mycotoxin alternariol. Toxicol Appl Pharmacol 271:64–71. https://doi.org/10.1016/j.taap.2013.05.002

Furuita H, Tanaka H, Yamamoto T, Suzuki N, Takeuchi T (2002) Effects of high levels of n-3 HUFA in broodstock diet on egg quality and egg fatty acid composition of Japanese flounder, *Paralichthys olivaceus*. Aquaculture 210:323–333. https://doi.org/10.1016/S0044-8486(01)00855-9

Harshavardhan MA, Aanand S, Stephen Sampath Kumar J, Senthilkumar V (2021) Comparative evaluation of commercial vegetable oil, fish oil, palm oil and groundnut oil as a lipid source in maturation and reproductive performance of fancy koi, Cyprinus carpio var koi. Aquaculture 545:737248. https://doi.org/10.1016/j.aquaculture.2021.737248

Herrera M, Mancera JM, Costas B (2019) The use of dietary additives in fish stress mitigation: comparative endocrine and physiological responses. Front Endocrinol 10:447. https://doi.org/10.3389/fendo.2019.00447

IFFO (2021) DATA. https://www.iffo.com/annual-report-2021

Islam MJ, Kunzmann A, Henjes J, Slater MJ (2021) Can dietary manipulation mitigate extreme warm stress in fish? The case of European seabass, *Dicentrarchus labrax*. Aquaculture 545: 737153. https://doi.org/10.1016/j.aquaculture.2021.737153

Islam MJ, Kunzmann A, Slater MJ (2022) Responses of aquaculture fish to climate change-induced extreme temperatures: a review. J World Aquac Soc 53:314–366. https://doi.org/10.1111/jwas.12853

Izquierdo MS, Fernandez-Palacios H, Tacon AGJ (2001) Effect of broodstock nutrition on reproductive performance of fish. Aquaculture 197(1–4):25–42. https://doi.org/10.1016/B978-0-444-50913-0.50006-0

Jannathulla R, Rajaram V, Kalanjiam R, Ambasankar K, Muralidhar M, Dayal JS (2019) Fishmeal availability in the scenarios of climate change: inevitability of fishmeal replacement in aquafeeds and approaches for the utilization of plant protein sources. Aquacult Res 50:3493–3506. https://doi.org/10.1111/are.14324

Jia R, Ma Q, Fan Y, Ji C, Zhang J, Liu T, Zhao L (2016) The toxic effects of combined aflatoxins and zearalenone in naturally contaminated diets on laying performance, egg quality and mycotoxins residues in eggs of layers and the protective effect of Bacillus subtilis biodegradation product. Food Chem Toxicol 90:142–150. https://doi.org/10.1016/j.fct.2016.02.010

Kestemont P, Henrotte E (2015) In: Kestemont P, Dabrowski K, Summerfelt RC (eds) Biology and culture of percid fishes. Springer, Dordrecht, pp 539–564

Kibria G, Nugegoda D, Rose G, Haroon AKY (2021) Climate change impacts on pollutants mobilization and interactive effects of climate change and pollutants on toxicity and bioaccumulation of pollutants in estuarine and marine biota and linkage to seafood security. Mar Pollut Bull 167:112364. https://doi.org/10.1016/j.marpolbul.2021.112364

King HR, Pankhurst NW (2004) Effect of maintenance at elevated temperatures on ovulation and luteinizing hormone releasing hormone analogue responsiveness of female Atlantic salmon (*Salmo salar*) in Tasmania. Aquaculture 233(1–4):583–597. https://doi.org/10.1016/j.aquaculture.2003.09.049

Lavens P, Lebegue E, Jaunet H, Brunel A, Dhert P, Sorgeloos P (1999) Effect of dietary essential fatty acids and vitamins on egg quality in turbot broodstocks. Aquacult Int 7:225–240. https://doi.org/10.1023/A:1009225028889

Liang MQ, Lu QK, Qian C, Zheng KK, Wang XX (2013) Effects of dietary n-3 to n-6 fatty acid ratios on spawning performance and larval quality in tongue sole *Cynoglossus semilaevis*. Aquacult Nutr 20(7):9–89. https://doi.org/10.1111/anu.12054

Maire E, Graham NAJ, MacNeil MA, Lam VWY, Robinson JPW, Cheung WWL, Hicks CC (2021) Micronutrient supply from global marine fisheries under climate change and overfishing. Curr Biol 31:4132–4138.e3. https://doi.org/10.1016/j.cub.2021.06.067

McBride RS, Somarakis S, Fitzhugh GR, Albert A, Yaragina NA, Wuenschel MJ, Alonso-Fernandez A, Basilone G (2015) Energy acquisition and allocation to egg production in relation to fish reproductive strategies. Fish Fish 16(1):23–57. https://doi.org/10.1111/faf.12043

Meunpol O, Meejing P, Piyatiratitivorakul S (2005) Maturation diet based on fatty acid content for male *Penaeus monodon* (Fabricius) broodstock. Aquacult Res 36:1216–1225

Migaud H, Bell G, Cabrita E, Mcandrew B, Davie A, Bobe J, Herráez MP, Carrillo M (2013) Gamete quality and broodstock management in temperate fish. Rev Aquac 5:S194. https://doi.org/10.1111/raq.12025

Rainuzzo JR, Reitan KI, Olsen Y (1997) The significance of lipids at early stages of marine fish: a review. Aquaculture 155(1–4):103–115. https://doi.org/10.1016/S0044-8486(97)00121-X

Rodriguez C, Cejas JR, Martin MV, Badia P, Samper M, Lorenzo A (1998) Influence of n-3 highly unsaturated fatty acid deficiency on the lipid composition of broodstock gilthead sea bream (*Sparus aurata*) and on egg quality. Fish Physiol Biochem 18:177–187. https://doi.org/10.1023/A:1007750218840

Schade FM, Clemmesen C, Mathias Wegner K (2014) Within- and transgenerational effects of ocean acidification on life history of marine three-spined stickleback (*Gasterosteus aculeatus*). Mar Biol 161:1667–1676. https://doi.org/10.1007/s00227-014-2450-6

Schwartz P, Thorpe KL, Bucheli TD, Wettstein FE, Burkhardt-Holm P (2010) Short- term exposure to the environmentally relevant estrogenic mycotoxin zearalenone impairs reproduction in fish. Sci Total Environ 409:326–333. https://doi.org/10.1016/j.scitotenv.2010.10.017

Schwartz P, Bucheli TD, Wettstein FE, Burkhardt-Holm P (2011) Life-cycle exposure to the estrogenic mycotoxin zearalenone affects zebrafish (*Danio rerio*) development and reproduction. Environ Toxicol 28(5):276–289. https://doi.org/10.1002/tox.20718

Servili A, Canario AVM, Mouchel O, Muñoz-Cueto JA (2020) Climate change impacts on fish reproduction are mediated at multiple levels of the brain-pituitary-gonad axis. Gen Comp Endocrinol 291:113439. https://doi.org/10.1016/j.ygcen.2020.113439

Vassallo-Agius R, Watanabe T, Yoshizaki G, Satoh S, Takeuchi T (2001) Quality of eggs and spermatozoa of rainbow trout fed an n-3 essential fatty acid-deficient diet and its effects on the lipid and fatty acid components of eggs, semen and livers fish. Science 2001(67):818–827

Volkoff H, London S (2018) Nutrition and reproduction in fish. In: Skinner MA (ed) Encyclopedia of reproduction, vol 6, 2nd edn. Elsevier, Amsterdam, pp 743–748

Watanabe T, Arakawa T, Kitajima C, Fujita S (1984) Effect of nutritional quality of broodstock diets on reproduction of red sea bream. Nippon Suisan Gakk 1984(50):495–501

Woźny M, Dobosz S, Obremski K, Hliwa P, Gomułka P, Łakomiak A, Rózyński R, Zalewski T, Brzuzan P (2015) Feed-borne exposure to zearalenone leads to advanced ovarian development and limited histopathological changes in the liver of premarket size rainbow trout. Aquaculture 448:71–81. https://doi.org/10.1016/j.aquaculture.2015.05.032

Woźny M, Obremski K, Jakimiuk E, Gusiatin M, Brzuzan P (2013) Zearalenone contamination in rainbow trout farms in north-eastern Poland. Aquaculture 416–417:209–211. https://doi.org/10.1016/j.aquaculture.2013.09.030

Woźny M, Obremski K, Zalewski T, Mommens M, Łakomiak A, Brzuzan P (2017) Transfer of zearalenone to the reproductive system of female rainbow trout spawners: a potential risk for aquaculture and fish consumers? Food Chem Toxicol 107:386–394. https://doi.org/10.1016/j.fct.2017.07.010

Woźny M, Dobosz S, Hliwa P, Gomułka P, Król J, Obremski K, Blahova J, Svobodova Z, Michalik O, Ocalewicz K, Brzuzan P (2020) Feed-borne exposure to zearalenone impairs reproduction of rainbow trout. Aquaculture 528:735522. https://doi.org/10.1016/j.aquaculture.2020.735522

Xu Y, Li W, Ding Z (2017) Polyunsaturated fatty acid supplements could considerably promote the breeding performance of carp. Eur J Lipid Sci Technol 119(5):1600183. https://doi.org/10.1002/ejlt.201600183