



Strategies to Mitigate Climate Change-Imposed Challenges in Fish Nutrition

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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

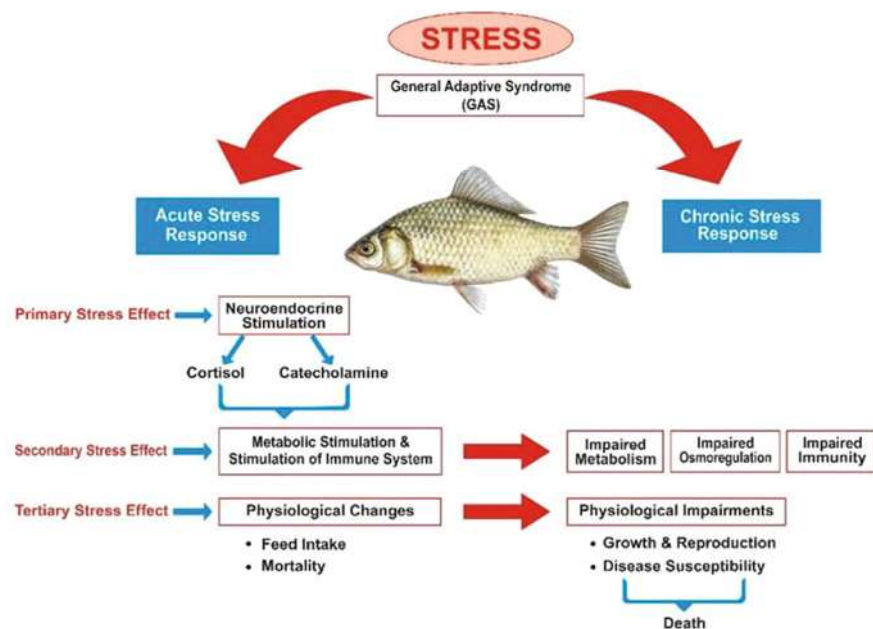


Fig. 1 Stress response and impacts on fish

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 immunocuticals, 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 Immunocuticals in Mitigating Temperature-Related Stress in Fish

Immunocuticals, 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 immunocuticals 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 immunocuticals 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 immunocuticals, 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 (Yukgehnash 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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Conflict of Interest The authors have no conflicts of interest to declare.

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