EISSN 2602-473X

AQUATIC SCIENCES AND ENGINEERING

Aquat Sci Eng 2024; 39(2): 121-129 • DOI: https://doi.org/10.26650/ASE20231341460

Review Article

A Review on the Impact of Thermal Stress on Fish Biochemistry

Prasun Roychowdhury[1,2], Mohammad Aftabuddin[1], Manoj Kumar Pati[2]

Cite this article as: Roychowdhury, P., Aftabuddin, M., & Pati, M.K. (2024). A review on the impact of thermal stress on fish biochemistry. *Aquatic Sciences and Engineering, 39(2),* 121-129. DOI: https://doi.org/10.26650/ASE20231341460

ABSTRACT

Fish are an important resource for humans, providing food, economic support, and ecological services. However, rising global temperatures and subsequent increases in their habitat water temperature, pose a significant challenge. We conducted a systematic review to understand the biochemical responses of thermal stress on fish. Stress can be acute (rapid exposure for a short duration) or chronic (repetitive long-term exposure). Stress responses occur at neurotransmitter and hormonal levels, progressing to peripheral and organism-wide effects. Prolonged stress leads to reduced growth, reproductive impairments, heightened infection susceptibility, and mortality. Elevated temperatures serve as abiotic stressors, triggering biotic stress responses. Fish employ strategies to cope with thermal stress, including altering gene expression, metabolite profiles, cellular signaling, and enzyme activity. Cumulative effects of thermal stress induce oxidative stress, causing cell death, organ failure, and mortality. Stressors increase the energy demand, prompting changes in hormonal, enzymatic, and biomolecular responses. Cortisol alters gene expression, stimulating glucose synthesis (gluconeogenesis). Other hormones (thyroid hormones, epinephrine, norepinephrine, insulin, glucagon) also play roles in the thermal stress response. Enzymes involved in metabolic pathways have optimal temperature and pH ranges altered by thermal stress. Heat shock proteins and warm acclimation proteins act as protective mechanisms by preserving the structural integrity of proteins, which is crucial for maintaining proper functionality and cellular responses. Further research is needed to expand on these molecular mechanisms to evaluate proper mitigation strategies.

Keywords: Fish stress, Global warming, Thermal stress, Biochemical responses, Molecular mechanism

ORCID IDs of the author:
P.R. 0000-0002-4522-2729;
M.A. 0000-0003-3135-0698;
M.K.P. 0000-0003-1197-0873

[1]Central Inland Fisheries Research Institute (CIFRI-ICAR), Barrackpore, India

[2]Aquaculture Management and Technology, Vidyasagar University, Midnapore, India

Submitted:
25.08.2023

Revision Requested:
24.10.2023

Last Revision Received:
18.01.2024

Accepted:
25.01.2024

Online Published:
04.03.2024

Correspondence:
Prasun Roychowdhury
E-mail:
prasun.bkp@gmail.com

INTRODUCTION

Importance of fishes

Fish are very important aquatic animals to humans as they provide different health benefits, economic support, and ecological services (FAO, 2016). As per the www.fishbase.de website, there are a total of 33,230 fish species in the world (Fishbase, 2020). Direct or indirect beneficial impacts of fish on the human population are numerous and have prevailed from ancient ages; only a few of these are discussed here. Fishes are important nutritional food for humans as well as for other animals. Fish are a low-cost protein source for humans and nearly 3.1 billion humans depend on fish to the tune of at least 20% of their total animal protein intake. Fish are the source of different essential amino acids such as lysine, valine, and functional amino acids, such as leucine and arginine (Ganguly et al., 2018). Fish are also a source of important vitamins, minerals, and other nutrients such as A, D, E, K, B12, sodium, potassium, magnesium, zinc, calcium, iron, copper, iodine, selenium, and fish oils (http://www.fao.org/fileadmin/user_upload/newsroom/docs/BlueGrowthNutritionRev2.pdf). Fish oils are rich in important PUFAs, such as linoleic acid, α-linolenic acid, arachidonic acid, EPA and DHA. Fish oils have different physiological benefits in several pathological conditions such as heart problems, atherosclerosis, rheumatoid arthritis, bipolar disorder, osteoporosis, asthma, etc. (Mohanty et al., 2019). Ornamental fish also are used in pet therapy to reduce mental depression (Gardiánová & Hejrová, 2015). Fish spas are also very popular nowadays (Riyaz & Arakkal, 2011). Fish are also used in the production of feed for other animals including other fish (Tacon & Metian, 2008).

Increment in water temperature

'Climate change' is a nightmare for the whole world and one of the most challenging hazards to be faced on the Earth in the coming future. Climate change results in a rise of the global surface temperature, known as 'Global warming'. The mean temperature of Earth's surface so far has risen by 1.4 °F over the last century and is expected to rise more (2 to 11.5 °F) over the coming hundred years (http://www.epa.gov/climatechange/basics/). Global warming is not only an increase in the temperature but also an alteration of different parameters of water bodies (Ficke et al., 2007, Brander, 2010). The surface temperature of the Earth has already increased (nearly +0.93 °C in the past 150 years) and is predicted to increase a few degrees more (1–4 °C) up to the end of this century (IPCC, 2007). Other than the increment in the Earth's surface temperature, experts have predicted some regional variations in temperatures (IPCC editor, 2012). Thus, impacts will vary in different parts of the globe. More events of extreme, abrupt, and frequent changes in temperature are documented in past decades (1991–2000) compared to earlier decades (1971–1990) (Dash & Mamgain, 2011). Different researchers (Diffenbaugh et al., 2007; Ray et al., 2012) also have found extreme events earlier. A heatwave was observed in Ahmedabad, India when the temperature rose to 46.8 °C during May 2010 (Azhar et al., 2014). Increments in the air temperature also led to a rise in the water temperature. Jurgelėnaitė and Jakimavičius (2014) have established a good positive correlation between air temperature and water temperature. The IPCC (2013) in their fifth assessment report estimated ocean warming by 0.09 to 0.13 °C per decade over the past 40 years. There will be an increment in the temperature of water bodies that will alter the habitat of different aquatic animals. Fishes are temperature-sensitive animals (poikilotherms); therefore, increments in the habitat temperature in the coming future beyond the adaptation capacity may exert abiotic stress among them.

STRESS BIOLOGY

General stress in animals

Cannon (1929) was the pioneer researcher who proposed the concept of stress as an "emotionally stimulation situation". Later, Selye (1936) explained the stress in the biological point of view. He demonstrated stress as a "non-specific pathological" response to different "noxious agents". However, several researchers encountered the concept of "the non-specific nature" of stress and proposed it is as highly specific (Mason, 1971; Pacak & Palkovitis, 2001). Stress is the discomfort state of the body under a threat where coordinated responses of physiological, biochemical, and behavioral processes cumulatively help the organism to overcome the situation (Chrousos & Gold, 1992). The initial response is to adapt to the situation by changing different biological processes of the body to a new normal situation in response to external as well as internal stimuli, which are cumulatively known as "allostatic load" (Schreck, 2001). The term "allostatic" denotes the body's capacity to attain stability amid change, with "load" signifying the toll or expense incurred by the body in adapting to stress (McEwen, 2013). Conceptually, stress can be defined as an alteration of physiological, biochemical (in the lower and higher organism), and mental (only in higher organisms) states due to different external (environmental factors), internal (body imbalance), or emotional stimuli that in the long-run effect performance and create physiological disorders, which every organism tries to avoid although it is nearly impossible.

Stress responses

Under stress, fish initially respond at the neurotransmitter and hormonal level (primary response) then at the peripheral level (secondary response) (Mazeaud et al., 1977), and finally to the whole organism or population level (tertiary responses) (Wodemeyer & McLeay, 1981). The primary responses are the "alarming stages" and two hormonal axes are involved in any kind of stress response in fish. The sympathetic-chromaffin (SC) axis and the hypothalamic-pituitary-interrenal (HPI) axis regulate oxygen uptake, transfer, and energy metabolisms (Wendelaar, 1997, Roychowdhury et al., 2020b). The secondary responses are the stages of "resistance". During that stage, fish try to engage all the available mechanisms to cope with the situation. The tertiary response of an organism is the "stage of exhaustion" where fish are unable to fight against the stress, reflected in their performance, and finally may cause even death (Roychowdhury et al., 2020a, Roychowdhury et al., 2020b). Therefore, the primary responses occur at a systemic level whereas secondary responses occur at the peripheral level, and the tertiary response affects the whole organism (Wodemeyer & McLeay, 1981). Once a fish receives stress stimuli, its sensory neurons in the brain activate the hypothalamus to release different hormones and neurotransmitters. Releasing hormones (RHs) such as CRH and TRH are the most important. These RHs act on the pituitary to release different hormones such as ACTH and α-MSH. ACTH further helps to release cortisol, an important hormone under stress. Cortisol is produced from an internal gland whereas catecholamines are produced in a chromaffin gland and interestingly both of them are found in the kidneys of fish (Milano et al., 1997). These hormones further alter the biochemistry, immunology, and physiology of fish under stress and induce the secondary responses (Weyts et al., 1999). These effects, in the long term, are reflected in fish performance as a reduction in growth, reproduction, susceptibility to infection, and ultimately mortality (Schreck et al., 2001).

Acute stress and chronic stress

Stress responses in fish depend on the types of stressors, the duration of exposure, the rate of introduction to stressors, and the amount of the stress (Barandica & Tort, 2008; Wedemeyer, 1997). Stresses are of two types, acute and chronic, based on the duration of exposure time. Acute stress involves rapid exposure for a short duration of exposure time (hours). Chronic stress is due to constant or repetitive exposure to the stressor for long periods (Barandica & Tort, 2008).

Acute stress is mainly the "fight or flight" response and is initiated mostly in the primary response. Acute stress in Black Sea trout

(*Salmo trutta labrax)* due to thermal exposure may involve an alteration in blood glucose, cortisol, total protein, serum ion concentrations, and lysozyme activity (Dengiz Balta et al., 2017). Acute stress is sometimes helpful for an organism. However, chronic stress can be viewed as repetitive exposure to stressors and the central nervous system (CNS) does not get sufficient time to recover (Sapolsky, 1996). It generally causes secondary and even tertiary responses (health issues). Under any kind of chronic stress, the body changes to 'a new normal' state. Chronic stress impacts nearly all physiological processes, and experimental conditions have been devised to induce such stress, revealing varying durations in different fish species. For instance, it necessitated 15 days in zebrafish (Chakravarty et al., 2013) and Nile tilapia (Volpato & Barreto, 2001), 28 days in rainbow trout (Moltesen et al., 2016), and 8 days in zebrafish (Golla et al., 2020). Intriguingly, chronic stress elicits a more intricate set of responses compared to acute stress. While acute stress predominantly triggers primary and secondary responses, chronic stress encompasses all three types of stress responses. This complexity underscores the multifaceted nature of physiological adaptations in animals under prolonged stress conditions (McEwen & Gianaros, 2011).

THERMAL STRESS IN FISH

In the earlier section, it was discussed that fishes are temperature-sensitive animals, therefore, an increment in the habitat temperature beyond the thermal tolerance capacity causes fish to feel abiotic stress. Thermal tolerance is the range of temperatures encompassing minimum to maximum levels where fish can survive and perform all their physiological functions. The upper-temperature tolerance limit (UTTL) of fish is the highest temperature up to which fish can survive (Daniel et al., 2008, Roychowdhury et al., 2019). The UTTL of fish depends on geographical location (Sorte et al., 2011), previous thermal history (Beitinger et al., 2000), transgenerational acclimatization (Donelson et al., 2012), the type of feed consumed (Kumar et al., 2014), and the rate of temperature increments (Camilo & Maria, 2006). The most commonly employed tools for studying the UTTL in fish are the lethal temperature maximum (LTmax) and critical temperature maximum (CTmax) (Beitinger et al., 2000). Thermal plasticity in fish refers to the capacity of fish species to adjust their physiological and behavioral traits in response to temperature changes (Comte & Olden, 2017). Fish exhibit thermal plasticity through alterations in metabolism, enzyme activity, gill function remodeling, changes in spawning time, and behavioral adaptations (Angiulli et al., 2020; Das et al., 2012; Farrell, 2009; Roychowdhury et al., 2020b). Parameters like warming temperature (WT) and thermal safety margin (TSM) are crucial for studying thermal plasticity in ectothermic animals (Becker & Genoway, 1979; Madeira et al., 2007). In fish physiology, aerobic space refers to the volume of oxygen available for aerobic metabolism, crucial for energy production (Jobling, 1995). Factors influencing this space include dissolved oxygen levels, gill efficiency, and metabolic rate (Farrell, 2009). Elevated water temperature often results in decreased dissolved oxygen (DO), leading to hypoxic conditions. Understanding aerobic space helps assess fish adaptation to environmental conditions and stressors (Eliason et al., 2013). The Temperature Coefficient (Q10) measures the temperature sensitivity of physiological or biochemical processes, indicating the rate of change with a 10-degree Celsius temperature increase. In the context of oxygen consumption in fish, the Q10 value describes how oxygen consumption rates vary with temperature changes. Researchers use Q10 values to understand thermal dependence in fish and other ectothermic organisms, providing insights into the temperature's influence on metabolic processes and aiding predictions of climate change impacts on fish physiology and ecology. Variations are observed among fish species based on their adaptations to specific environmental conditions (Claireaux & Lefrançois, 2007; Farrell, 2009; Pörtner & Farrell, 2008).

'Fight or flight' is the initial strategy for most organisms in a hostile environment. Fish try to move toward the more preferable environment but if they fail to do so, they will feel stress (Kovach et al., 2012). A warmer temperature is abiotic stress that causes different biotic stress in organisms (Nakano et al., 2014). However, data on the impacts of thermal stress on different biochemical pathways are limited in carp fish. Therefore, previous literature on thermal stresses on fish and other organisms needs to be reviewed to understand the thermal stress biology of an organism. Besides, this information can help to design proper methodology and selection of different biomolecules expected to be altered under thermal stress in fish. The process of adaption and stress are difficult to distinguish at the initial stages as fish try to fight the stress by altering their biochemical pathways in higher temperatures. Patterns of the expression of different biomolecules are changed initially due to adaptation and later on due to stress (Bijlsma & Loeschcke, 2005). The consequence of an event depends on the extent of stress, the genetic makeup of the organisms, and previous history of exposure (Beitinger et al., 2000). A higher temperature is known to increase the kinetic properties of molecules causing a higher diffusion rate for micro-molecules (Bag et al., 2014) and denaturation of macromolecules (Wu, 1995). Maintenance of the native three-dimensional structure of a protein is very much essential for proper functioning, and interaction with other biomolecules involved in cellular response, and any randomness beyond certain limits may lead to cellular death (Nakamura & Lipton, 2009). Fish try to cope with the situation by changing gene expression patterns and are reflected in alteration in metabolites (biomolecules), cellular signaling systems (hormones and others), and enzyme activity (Lancaster et al., 2016). The stress is tolerable to a certain extent after the performance of the species drops (La & Cooke, 2011; Pörtner & Knust, 2007). Due to the cumulative impacts of the different effects of thermal stress, oxidative stress begins to occur and results in cellular death, organ failure and ultimately death of the organism (Figure 1).

BIOCHEMICAL MECHANISM

Any kind of stressor increases the requirement of physiological energy that can be fulfilled by alteration of hormonal, enzymes and bimolecular responses. In general, glucose, triglycerides and protein act as energy molecules depending upon the nature and quantity of energy needed (Mergenthaler et al., 2013). Glucose serves as an immediate energy source, while triglycerides provide major energy, and protein provides energy during hun-

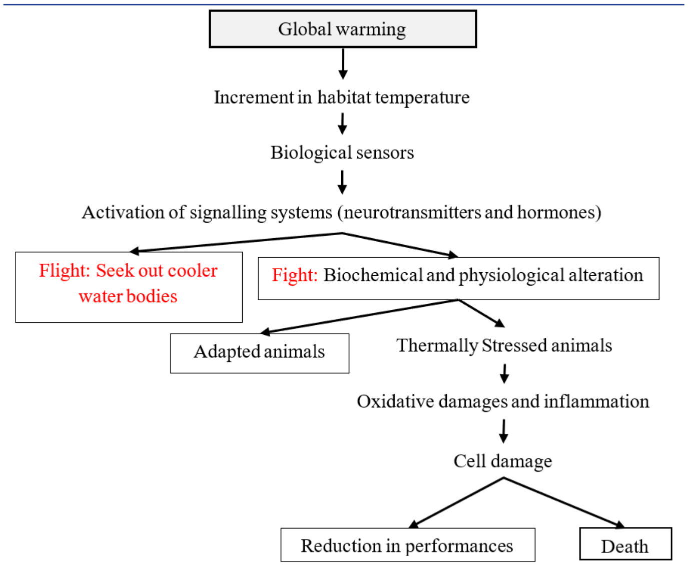

Figure 1. Conceptual representation of the consequences of thermal stress in fish.

ger or in some physiological disorders and stress. In stressful situations, fishes try to increase blood glucose to provide more energy to vital organs including the brain by changing the metabolism of biomolecules under the control of hormones (Mergenthaler et al., 2013). The steroid hormone, cortisol alters the pattern of gene expression (transcription level) and increases the expression of the different enzymes required for the synthesis of new glucose molecules (gluconeogenesis) (Babitha & Peter, 2010; Vijayan et al., 1997) and breakdown of the stored glycogen (glycogenolysis) (Vijayan et al., 1993 and 1996) during stress to increase blood glucose concentration in serum. Cortisol converts the non-essential proteins of muscle to amino acids and transports them through the blood to the liver for gluconeogenesis (Vijayan et al., 1993; Vijayan & Moon, 1994; Freeman & Idler, 1973). Cortisol is also documented to mobilize stored lipids in teleost species (Dave et al., 1979). Thyroid hormones, T3 and T4 are produced in the thyroid gland and normally maintain a positive nitrogen balance, but T3 inhibits protein synthesis in higher concentrations (Murray et al., 1996). Like cortisol, thyroid hormones are also known to act at the transcriptional level and modify its function or 'fine-tune' the actions of cortisol and adrenaline in a stressful situation (Peter, 2011). Epinephrine and norepinephrine, released from chromaffin cells, are recognized by their immediate elevation of plasma glucose levels (Arends et al., 1999; Ruane et al., 2001). Their roles encompass enhancing glucagon secretion, facilitating glycogen breakdown (glycogenolysis), initiating new glucose synthesis (gluconeogenesis), mobilizing fatty acids (beta oxidation), and concurrently suppressing insulin production, glycogen synthesis (glycogenesis), and glucose breakdown (glycolysis) (Nelson & Cox, 2001). Their primary targets are muscle, adipose tissue, and liver, and increase the supply of oxygen to tissue by increasing heart rate, blood pressure, and respiratory passage (Nelson & Cox, 2001). Cortisol plays a role mostly in chronic stress, while epinephrine and norepinephrine act as emergency hormones and are involved in immediate responses. Insulin and glucagon maintain glucose homeostasis in blood in normal conditions but their direct involvement in heat stress is limited. Insulin increases the utilization of glucose by increasing glucose transportation in cells and increasing the rate of glycolysis in extrahepatic tissues and glycogenesis in hepatic tissue but glucagon plays the counter role of insulin by producing glucose through gluconeogenesis and glycogenolysis thus increasing blood glucose (Nelson & Cox, 2001).

Blood glucose is used to monitor general stress for different species. Energy-rich molecules like ATP, GTP, phosphocreatine, succinate, and ketone bodies are also known to play an important role during thermal stress and can be used as possible markers for thermal stress (Dijk et al., 1999). Metabolism of biomolecules is under hormonal control necessitating monitoring of the hormones cortisol, T3, T4, epinephrine, norepinephrine, insulin, and glucagon during stress.

Every enzyme has an optimum temperature and pH and thermal stress is known to change these parameters for cold-blooded fish. Enzymes involved in the metabolism of energy-rich biomolecules alter their activity by changing their concentration (expression) or affinity (modification) towards the substrate under a stressed condition. Enzymes catalyzing the irreversible steps of carbohydrate metabolism (hexokinase, phosphofructokinase1, pyruvate kinase, citrate synthase, glucose 6 phosphatase, fructose-1,6 bis-phosphatase, etc.), protein metabolism (glutamate-pyruvate transaminase and glutamate-oxaloacetate transaminase), lipid metabolism (lipase), and creatinine metabolism (creatinine kinase) are important from this perspective (Dhanasiri et al., 2013, Abbaraju & Rees, 2012; Ton et al., 2003).

Thermodynamics explains life as the maintenance of organized cellular structures through energy generated by oxidizing energy-rich nutrients by enzyme(s) that act at an optimum temperature under the control of hormones. Temperature changes directly affect these activities. Proteins are the mediators of diverse types of cellular functions (Alberts et al., 2002) including enzymatic action to scale formation, body growth to reproduction, and digestion to excretion. The function of a protein depends on its native structure that gets denatured due to the rise in temperature causing more vibration in molecules and related disturbance. Heat shock proteins (Hsps), which are highly conserved, are the molecular chaperones required for the proper folding of the protein and are also involved in protein transport to cellular compartments (Alberts et al., 2002; Shi & Thomas, 1992). At higher temperatures Hsps refold the denatured protein to its original native structure and the heat shock factor (Hsf) induces the expression of various Hsps in the process (Wu, 1995). There are various types of Hsps within the cell such as Hsp10, HspB group (Hsp27, hspB1, hspB6), HspA group (Hsp70, Hsp71, Hsp72, Hsp78), HspC group (Hsp90, hsp94), Hsp40, Hsp60, Hsp104, and Hsp110 (Antonova et al., 2007; Benjamin & McMillan, 1998; Li & Srivastava, 2004; McLemore et al., 2005; Salinthone et al., 2008; Schlesinger, 1990). Hsp30, Hsp27, and Hsp47 are identified in goldfish (Wang et al., 2007) while Hsp78 and Hsp100 are found in *Poeciliopsis lucida* (Norris et al., 1995). Warm acclimation protein (wap) is another candidate that plays an important role during heat stress (Kikuchi et al., 1997) (Figure 2).

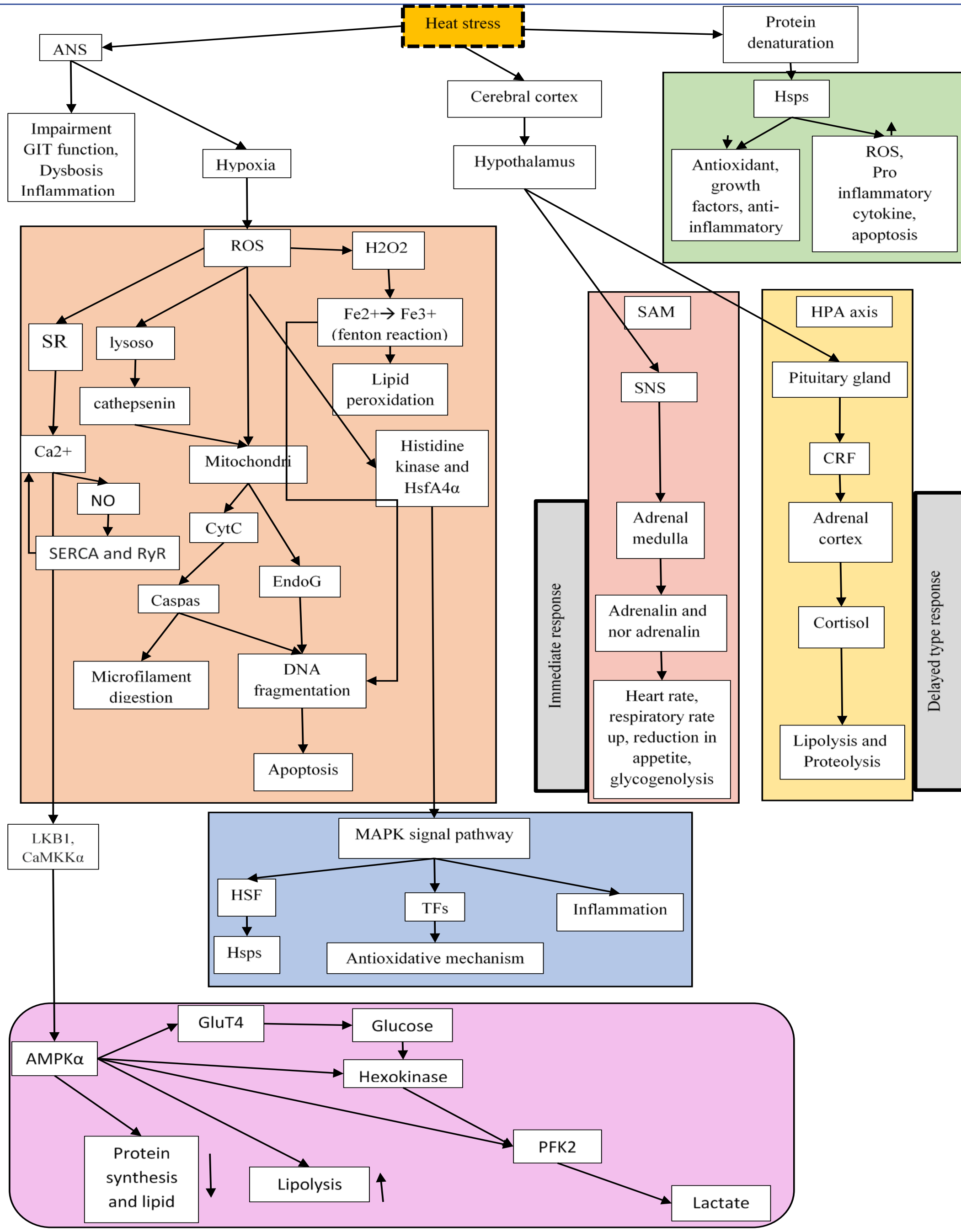

Figure 2. Impact of thermal stress at the molecular biology level (Antoun et al., 2017; Cui et al., 2016; Kourtis and Tavernarakis, 2011; Kültz, 2015; Xing et al., 2019).

Numerous experiments have been conducted to study the impacts of heat stress on fish and a few of them are cited here: rahu (Akhtar et al., 2013; Kumar et al., 2015; Mohapatra et al., 2014), common carp (Ouellet, et al., 2013), rainbow trout (Recsetar et al., 2012), blenny species (Camilo and Maria, 2006), salmon (Dengiz Balta et al., 2017; Nakano et al., 2014), *Channa punctatus* (Kaur et al., 2005), pacific sardine (Kaur et al., 2005), and *Danio dangila* and *Brachydanio rerio* (Majhi & Das, 2013). The selected temperatures for treatments were mostly sub-lethal with no fish death (Das et al., 2002; Das et al., 2005; Nakano et al., 2014). These experiments were mainly focused on the recovery responses (Kumar et al., 2015), adaptation strategies (Das, 2002), gene expression pattern (Ouelle et al., 2013), oxidation-reduction state (Nakano et al., 2014), thermal tolerance, growth and oxygen consumption (Das et al., 2005), and search for bio-markers (Purohit et al., 2014). Different experimental conditions were used for warmer water exposure to induce heat stress in fish. The three main determinants to introduce thermal stress to fish are the amount of temperature, duration of exposure, and rates of temperature increment, and all of them varied in the experiments (Akhtar et al., 2013; Das et al., 2005; Dengiz Balta et al, 2017; Kaur et al., 2005; Kumar et al., 2015; Majhi & Das, 2013; Mohapatra et al., 2014; Nakano et al., 2014; Recsetar et al., 2012). Fish may feel both acute stress and chronic stress based on events that will occur in future (IPCC, 2014). Different researchers have studied the impacts of both acute and chronic thermal stress among other animals including fish (Hernández-López et al., 2018) but data is very limited for IMC. Thermal stress is expected to alter the different physiological and biochemical processes of the body and that may be reflected in different pathways and performance of fish (Figure 3).

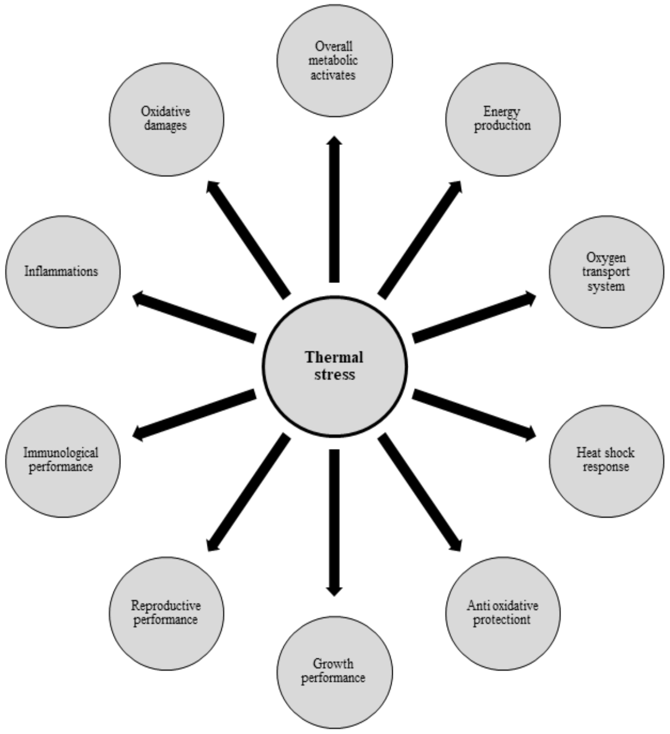

Figure 3. Abiotic thermal stress affects different physiological pathways (Aftabuddin et al., 2017; Aftabuddin and Roychowdhury, 2019).

DISCUSSION

The review revealed that thermal stress has substantial effects on fish, leading to reduced growth, reproductive impairments, increased susceptibility to infections, and even mortality. These consequences can have profound ecological and economic implications, considering the vital role of fish in providing food, supporting economies, and maintaining ecosystem balance. The study highlights the distinction between acute and chronic stressors, with acute stress resulting from short-term rapid exposure and chronic stress arising from long-term repetitive exposure. Understanding this differentiation is crucial for developing effective strategies to mitigate the impacts of thermal stress on fish populations. The elevated water temperatures associated with global warming act as abiotic stressors, triggering various biotic stress responses in fish. It was observed that fish employ a range of mechanisms to cope with thermal stress, including alterations in gene expression patterns, metabolite profiles, cellular signaling pathways, and enzyme activity. These adaptive responses enable fish to maintain their physiological balance and attempt to counteract the detrimental effects of thermal stress. However, the cumulative impact of thermal stress can induce oxidative stress, leading to cellular death, organ failure, and ultimately mortality. This highlights the urgent need to address the challenges posed by rising temperatures and the associated thermal stress on fish populations. The study emphasizes the role of hormonal, enzymatic, and biomolecular responses in the fish's attempt to meet the increased energy demands caused by stressors. Hormones such as cortisol play a significant role in altering gene expression and stimulating glucose synthesis through gluconeogenesis. Other hormones, including thyroid hormones, epinephrine, norepinephrine, insulin, and glucagon, are also involved in the fish's response to thermal stress. Enzymes associated with metabolic pathways in fish have optimal temperature and pH ranges that can be altered by thermal stress. Maintaining the proper structure and functionality of proteins is crucial for cellular responses and overall fish health. Heat shock proteins and warm acclimation proteins act as protective mechanisms, helping to preserve protein integrity and mitigate the adverse effects of thermal stress.

The findings of this systematic review emphasize the importance of further research to enhance our understanding of the molecular mechanisms underlying these responses. Such knowledge can guide the development of targeted conservation and management strategies to safeguard fish populations in the face of a rapidly changing environment.

Ethics Committee Approval: As this is a review paper, there is no requirement for ethics approval or consent.

Consent for Publication: The authors have provided their consent for publication.

Acknowledgements: The authors would like to express their gratitude to Dr. M. K. Das (former Principal Investigator), Dr. A. P. Sharma (former Principal Investigator), Dr. U.K. Sarkar (former Principal Investigator), Dr. M. Naskar (former Co-Investigator) of the NICRA project, and Dr. M. A. Hassan (Principal Scientist and in-charge of Fish Feed laboratory) and his team members of ICAR-Central Inland Fisheries Research Institute (CIFRI), Barrackpore, India, for their necessary support. The authors would also like to express their gratitude to Mrs. Sutapa Acharya (Assistant Teacher) for her assistance in correcting the English. The authors acknowledge the funding support provided by the Indian Council of Agricultural Research, New Delhi, under the National Innovations on Climate Resilient Agriculture (NICRA) research program.

Conflict of interest: None of the authors has any conflict of interest to declare.

Author Contribution: This review is part of the first author's Ph.D. thesis, and he conducted most of the work for manuscript preparation. The other two authors are the Ph.D. supervisors; they have provided scientific input and assisted in the preparation of the manuscript.

Ethical Statement: We certify that this is our original research work and it has neither been submitted or published elsewhere as a whole or in part. The authors are responsible for all the data and content in the Manuscript.

Declaration of Generative Ai in Scientific Writing: During the preparation of this work the author(s) used [https://chat.openai.com/] in order to improve English language such as checking grammar, spelling and for finding some references. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Data Availability Statement: This is a review article so data is available from the references.

Funding: There is no funding to declare.

REFERENCES

Abbaraju, N. V., & Rees, B. B. (2012). Effects of dissolved oxygen on glycolytic enzyme specific activities in liver and skeletal muscle of *Fundulus heteroclitus*. *Fish Physiology and Biochemistry*, 38(3), 615-624.

Aftabuddin, M., & Roychowdhury, P. (2019). Thermal effect on physio-biochemical aspects of fishes and thermal tolerance under changing climatic scenario. *Perspectives on Climate Change and Inland Fisheries in India*, 258.

Aftabuddin, M., Roychowdhury, P., & Sarkar, U. K. (2017). Understanding Thermal Tolerance of Potential Fish in the changing climatic environment. *Indian Farming*, 67(3).

Akhtar, M. S., Pal, A. K., Sahu, N. P., Ciji, A., Meena, D. K., Das, P. (2013). Physiological responses of dietary tryptophan fed *Labeo rohita* to temperature and salinity stress. *Journal of Animal Physiology and Animal Nutrition*, 97(6), 1075-1083.

Alberts, B., Johnson, A., & Lewis, J. (2002). *In Molecular Biology of the Cell* (4th edition). New York: Garland Science

Angiulli, E., Pagliara, V., Cioni, C., Frabetti, F., Pizzetti, F., Alleva, E., & Toni, M. (2020). Increase in environmental temperature affects exploratory behaviour, anxiety and social preference in *Danio rerio*. *Scientific Reports*, 10(1), 5385.

Antonova, G., Lichtenbeld, H., Xia, T., Chatterjee, A., Dimitropoulou, C., & Catravas, J. D. (2007). Functional significance of hsp90 complexes with NOS and sGC in endothelial cells. *Clinical Hemorheology and Microcirculation*, 37(1-2), 19-35.

Antoun, M., Edwards, K. M., Sweeting, J., & Ding, D. (2017). The acute physiological stress response to driving: A systematic review. *PloS One*, 12(10), e0185517.

Arends, R. J., Mancera, J. M., Munoz, J. L., Bonga, S. W., & Flik, G. (1999). The stress response of the gilthead sea bream (*Sparus aurata L.*) to air exposure and confinement. *Journal of Endocrinology*, 163(1), 149.

Azhar, G. S., Mavalankar, D., Nori-Sarma, A., Rajiva, A., Dutta, P., Jaiswal, A., ... & Hess, J. J. (2014). Heat-related mortality in India: Excess all-cause mortality associated with the 2010 Ahmedabad heat wave. *PLoS One*, 9(3), e91831.

Babitha, G. S., & Peter, M. S. (2010). Cortisol promotes and integrates the osmotic competence of the organs in North African catfish (*Clarias gariepinus Burchell*): Evidence from in vivo and in situ approaches. *General and Comparative Endocrinology*, 168(1), 14-21.

Bag, N., Yap, D. H. X., & Wohland, T. (2014). Temperature dependence of diffusion in model and live cell membranes characterized by imaging fluorescence correlation spectroscopy. *Biochimica et Biophysica Acta (BBA) Biomembranes*, 1838(3), 802-813.

Barandica, C. L. M. & Tort, L. (2008). Neuroendocrinología e inmunología de la respuesta al estrés en peces. *Revista de la Academia Colombiana de Ciencias*, 32(123), 267-284.

Becker, D. C., & Genoway, R. G. (1979). Evaluation of the critical thermal maximum for determining thermal tolerance of freshwater fish. *Environmental Biology of Fishes*, 4(4), 245–256.

Beitinger, T. L., Bennett, W. A., & McCauley, R. W. (2000). Temperature tolerances of North American freshwater fishes exposed to dynamic changes in temperature. *Environmental Biology of Fishes*, 58(3), 237-275.

Benjamin, I. J., & McMillan, D. R. (1998). Stress (heat shock) proteins: molecular chaperones in cardiovascular biology and disease. *Circulation Research*, 83(2), 117-132.

Bijlsma, R., & Loeschcke, V. (2005). Environmental stress, adaptation and evolution: an overview. *Journal of Evolutionary Biology*, 18(4), 744-749.

Brander, K. (2010). Impacts of climate change on fisheries. *Journal of Marine Systems*, 79(3- 4), 389-402.

Camilo, M., & Maria, F.M. (2006). Effect of the rate of temperature increase of the dynamic method on the heat tolerance of fishes. *Journal of Thermal Biology*, 31(4), 337-44.

Cannon, W. B. (1929). Organization for physiological homeostasis. *Physiological Reviews*, 9(3), 399-431.

Chakravarty, S., Reddy, B. R., Sudhakar, S. R., Saxena, S., Das, T., Meghah, V., ... & Idris, M. M. (2013). Chronic unpredictable stress (CUS)-induced anxiety and related mood disorders in a zebrafish model: altered brain proteome profile implicates mitochondrial dysfunction. *Plos One*, 8(5), e63302.

Chrousos, G. P., & Gold, P. W. (1992). The concepts of stress and stress system disorders: overview of physical and behavioral homeostasis. *Jama*, 267(9), 1244-1252.

Comte, L., & Olden, J. D. (2017). Evolutionary and environmental determinants of freshwater fish thermal tolerance and plasticity. *Global Change Biology*, 23(2), 728-736.

Cui, Y., Hao, Y., Li, J., Bao, W., Li, G., Gao, Y., & Gu, X. (2016). Chronic Heat Stress Induces Immune Response, Oxidative Stress Response, and Apoptosis of Finishing Pig Liver: A Proteomic Approach. *International Journal of Molecular Sciences*, 17(5), 393.

Daniel, G. B., Derek, P. T., & Boris, W. (2008). Effects of Temperature on Global Patterns of Tuna and Billfish Richness. *Marine Ecology Progress Series*, 355, 267–276.

Das, M. K., Dutta, T., Acharya, S., & Bhowmick, S. (2002). Sublethal temperature stress in juvenile Labeo rohita (Ham-Buch.) and Rita rita (Ham.): some physiological changes. *Indian Journal of Experimental Biology*, 40(5), 589–593.

Das, M. K., Srivastava, P. K., Dey, S., & Rej, A. (2012). Impact of temperature and rainfall alterations on spawning behavior of Indian major carps and consequence on fishers' income in Odisha. *Journal of Inland Fisheries Society of India*, 44(2), 1-11.

Das, T., Pal, A. K., Chakraborty, S. K., Manush, S. M., Sahu, N. P., & Mukherjee, S. C. (2005). Thermal tolerance, growth and oxygen consumption of *Labeo rohita* fry (Hamilton, 1822) acclimated to four temperatures. *Journal of Thermal Biology*, 30(5), 378-383.

Dash, S. K., & Mamgain, A. (2011). Changes in the frequency of different categories of temperature extremes in India. *Journal of Applied Meteorology and Climatology*, 50(9), 1842-1858.

Dave, G., Johansson-Sjöbeck, M. L., Larsson, Å., Lewander, K., & Lidman, U. (1979). Effects of cortisol on the fatty acid composition of the total blood plasma lipids in the European eel, *Anguilla anguilla L. Comparative Biochemistry and Physiology Part A*: Physiology, 64(1), 37-40.

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). *Turkish Journal of Veterinary & Animal Sciences*, 41(3), 400-406

Dhanasiri, A. K., Fernandes, J. M., & Kiron, V. (2013). Liver transcriptome changes in zebrafish during acclimation to transport-associated stress. *PLoS One*, 8(6), e65028.

Diffenbaugh, N. S., Pal, J. S., Giorgi, F., & Gao, X. (2007). Heat stress intensification in the Mediterranean climate change hotspot. *Geophysical Research Letters*, 34(11).

Dijk, P. L., Tesch, C., Hardewig, I., & Portner, H. O. (1999). Physiological disturbances at critically high temperatures: a comparison between stenothermal Antarctic and eurythermal temperate eelpouts (Zoarcidae). *Journal of Experimental Biology*, 202(24), 3611-362.

Donelson, J. M., Munday, P. L., McCormick, M. I., & Pitcher, C. R. (2012). Rapid transgenerational acclimation of a tropical reef fish to climate change. *Nature Climate Change*, 2(1), 30-32.

Eliason, E. J., Clark, T. D., Hague, M. J., Hanson, L. M., Gallagher, Z. S., Jeffries, K. M., ... & Hinch, S. G. (2013). Differences in thermal tolerance among sockeye salmon populations. *Science*, 342(6159), 1098-1101.

FAO. (2016). In FAO year book, 2014 Fishery and Aquaculture statistics (pp.105). *Food and Agriculture Organisation of the United Nations*, Rome, Italy.

Farrell, A. P. (2009). *In Encyclopedia of Fish Physiology: From Genome to Environmen*t. Academic Press.

Ficke, A. D., Myrick, C. A., & Hansen, L. J. (2007). Potential impacts of global climate change on freshwater fisheries. *Reviews in Fish Biology and Fisheries*, 17(4), 581-613.

Fishbase. (2020). https://www.fishbase.se/Country/CountryChecklist.php?what=list&trpp=50&c_code=356&cs ub_code=&cpresence=Reported&sortby=alpha2&ext_CL=on&ext_pic=on&vhabitat=all2

Freeman, H. C., & Idler, D. R. (1973). Effects of corticosteroids on liver transaminases in two salmonids, the rainbow trout (*Salmo gairdnerii*) and the brook trout (Salvelinus fontinalis). *General and Comparative Endocrinology*, 20(1), 69-75.

Ganguly, S., Mahanty, A., Mitra, T., Mohanty, S., Das, B. K., & Mohanty, B. P. (2018). Nutrigenomic studies on hilsa to evaluate flesh quality attributes and genes associated with fatty acid metabolism from the rivers Hooghly and Padma. *Food Research International*, 103, 21-29.

Gardiánová, I., & Hejrová, P. (2015). The use of small animals–mammals, birds, fish in zootherapy. *Kontakt*, 17(3), e171-e176.

Golla, A., Østby, H., & Kermen, F. (2020). Chronic unpredictable stress induces anxiety-like behaviors in young zebrafish. *Scientific Reports*, 10(1), 1-10.

Hernández-López, J. R., Hernández-Rodríguez, M., Rivas-Manzano, P., & Bückle-Ramirez, L. F. (2018). Thermal Effect of Acute and Chronic Stress on Hepatic and Renal Tissue of the Pacific Sardine, Sardinops sagax caeruleus (Jenyns, 1842). *International Journal of Morphology*, 36(1), 212-220.

IPCC editor. (2012). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

IPCC. (2007). Climate Change: The Physical Science Basis. Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

IPCC. (2013). Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T. F. D., Qin, G. K., Plattner, M., Tignor, S. K., Allen, J., Boschung, A., … Midgley, P. M. (Eds.). Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

IPCC. (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, Pachauri, R. K., and Meyer, L. A. (Eds.). Geneva, Switzerland: IPCC.

Jobling, M. (1995).*In Environmental Biology of Fishes*. Chapman & Hall.

Jurgelėnaitė, A., & Jakimavičius, D. (2014). Prediction of river water temperature and its dependence on hydro-meteorological factors. *Environmental Research, Engineering and Management*, 68(2).

Kaur, M., Atif, F., Ali, M., Rehman, H., & Raisuddin, S. (2005). Heat stress-induced alterations of antioxidants in the freshwater fish *Channa punctata Bloch*. *Journal of Fish Biology*, 67(6), 1653-1665.

Kikuchi, K., Watabe, S., & Aida, K. (1997). The Wap65 gene expression of goldfish (Carassius auratus) in association with warm water temperature as well as bacterial lipopolysaccharide (LPS). *Fish Physiology and Biochemistry*, 17(1-6), 423-432.

Kourtis, N., & Tavernarakis, N. (2011). Cellular stress response pathways and ageing: intricate molecular relationships. *The EMBO Journal*, 30(13), 2520–2531.

Kovach, R. P., Gharrett, A. J., & Tallmon, D. A. (2012). Genetic change for earlier migration timing in a pink salmon population. *Proceedings of the Royal Society B: Biological Sciences*, 279(1743), 3870-3878.

Kültz, D. (2015). Physiological mechanisms used by fish to cope with salinity stress. *Journal of Experimental Biology*, 218(12), 1907-1914.

Kumar, N., Minhas, P. S., Ambasankar, K., Krishnani, K. K., & Rana, R. S. (2014). Dietary lecithin potentiates thermal tolerance and cellular stress protection of milk fish (*Chanos Chanos*) reared under low dose endosulfan-induced stress. *Journal of Thermal Biology*, 46, 40-46.

Kumar, P., Pal, A. K., Sahu, N. P., Jha, A. K., & Priya, P. (2015). Biochemical and physiological stress responses to heat shock and their recovery in *Labeo rohita* fingerlings. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*, 85(2), 485-490.

La, V. T., & Cooke, S. J. (2011). Advancing the science and practice of fish kill investigations. *Reviews in Fisheries Science*, 19(1), 21-33.

Lancaster, L. T., Dudaniec, R. Y., Chauhan, P., Wellenreuther, M., Svensson, E. I., & Hansson, B. (2016). Gene expression under thermal stress varies across a geographical range expansion front. *Molecular Ecology*, 25(5), 1141-1156.

Li, Z., & Srivastava, P. (2004). In *Heat-shock proteins Current protocols in immunology*, edited by John E Coligan [et al.].

Madeira, C., Mendonça, V., Leal, M. C., Flores, A. A., Cabral, H. N., Diniz, M. S., & Vinagre, C. (2017). Thermal stress, thermal safety margins and acclimation capacity in tropical shallow waters-An experimental approach testing multiple end-points in two common fish. *Ecological Indicators*, 81, 146-158.

Majhi, S. K., & Das, S. K. (2013). Thermal tolerance, oxygen consumption and stress response in *Danio dangila* and *Brachydanio rerio* (Hamilton, 1822) acclimated to four temperatures. *Turkish Journal of Fisheries and Aquatic Sciences*, 13(2), 359-365.

Mason, J. W. (1971). A re-evaluation of the concept of 'non-specificity'in stress theory. *In Principles, Practices, and Positions in Neuropsychiatric Research* (pp. 323-333).

Mazeaud, M. M., Mazeaud, F., & Donaldson, E. M. (1977). Primary and secondary effects of stress in fish: some new data with a general review. *Transactions of the American Fisheries Society*, 106(3), 201-212.

McEwen, B. S. (2013). Allostasis and allostatic load: implications for neuropsychopharmacology. *Stress and the Brain*, 2-18.

McEwen, B. S., & Gianaros, P. J. (2011). Stress- and allostasis-induced brain plasticity. *Annual Review of Medicine*, 62, 431–445.

McLemore, E. C., Tessier, D. J., Thresher, J., Komalavilas, P., & Brophy, C. M. (2005). Role of the small heat shock proteins in regulating vascular smooth muscle tone. *Journal of the American College of Surgeons*, 201(1), 30-36.

Mergenthaler, P., Lindauer, U., Dienel, G. A., & Meisel, A. (2013). Sugar for the brain: the role of glucose in physiological and pathological brain function. *Trends in Neurosciences*, 36(10), 587-597.

Milano, E. G., Basari, F., & Chimenti, C. (1997). Adrenocortical and adrenomedullary homologs in eight species of adult and developing teleosts: morphology, histology, and immunohistochemistry. *General and Comparative Endocrinology*, 108(3), 483-496.

Mohanty, B. P., Mahanty, A., Ganguly, S., Mitra, T., Karunakaran, D., & Anandan, R. (2019). Nutritional composition of food fishes and their importance in providing food and nutritional security. *Food Chemistry*, 293, 561-570.

Mohapatra, S., Chakraborty, T., Prusty, A. K., PaniPrasad, K., & Mohanta, K. N. (2014). Beneficial effects of dietary probiotics mixture on hemato-immunology and cell apoptosis of *Labeo rohita* fingerlings reared at higher water temperatures. *Plos One*, 9(6), e100929.

Moltesen, M., Laursen, D. C., Thörnqvist, P. O., Andersson, M. Å., Winberg, S., & Höglund, E. (2016). Effects of acute and chronic stress on telencephalic neurochemistry and gene expression in rainbow trout (*Oncorhynchus mykiss*). *Journal of Experimental Biology*, 219(24), 3907-3914.

Murray, R. K., Granner, D. K., Mayes, P. A., & Rodwell, V. W. (1996). *In Harper's Illustrated Biochemistry (24th ed.)* (pp. 537). Appleton & Lange, Stamford, CT. ISBN 0-8385-3612-3.

Nakamura, T., & Lipton, S. A. (2009). Cell death: protein misfolding and neurodegenerative diseases. *Apoptosis*, 14(4), 455-468.

Nakano, T., Kameda, M., Shoji, Y., Hayashi, S., Yamaguchi, T., & Sato, M. (2014). Effect of severe environmental thermal stress on redox state in salmon. *Redox Biology*, 2, 772-776.

Nelson, D. L., & Cox, M. M., (2001). *Lehninger principles of biochemistry*. Macmillan.

Norris, C. E., diIorio, P. J., Schultz, R. J., & Hightower, L. E. (1995). Variation in heat shock proteins within tropical and desert species of poeciliid fishes. *Molecular Biology and Evolution*, 12(6), 1048-1062.

Ouellet, V., Pierron, F., Mingelbier, M., Fournier, M., Fournier, M., & Couture, P. (2013). Thermal Stress Effects on Gene Expression and Phagocytosis in the Common Carp (*Cyprinus Carpio*): a Better Understanding of the Summer 2001 st. Lawrence River Fish Kill. *The Open Fish Science Journal*, 6(1).

Pacak, K., & Palkovits, M. (2001). Stressor specificity of central neuroendocrine responses: implications for stress-related disorders. *Endocrine Reviews*, 22(4), 502-548.

Peter, M. S. (2011). The role of thyroid hormones in stress response of fish. *General and Comparative Endocrinology*, 172(2), 198-210.

Pörtner, H. O., & Knust, R. (2007). Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science*, 315(5808), 95-97.

Purohit, G. K., Mahanty, A., Suar, M. Sharma, A. P., Mohanty, B. P., & Mohanty, S. (2014). Investigating hsp gene expression in liver of *Channa striatus* under heat stress for understanding the upper thermal acclimation. *BioMed Research International*, 381719, 1-10.

Ray, K. A. T., Apte, N. Y., & Chicholikar, J.R. (2012). *In Climate of Ahmedabad.* Meteriological Center Ahmedabad, Ahmedabad.

Recsetar, M. S., Zeigler, M. P., Ward, D. L., Bonar, S. A., & Caldwell, C. A. (2012). Relationship between fish size and upper thermal tolerance. *Transactions of the American Fisheries Society*, 141(6), 1433-1438.

Riyaz, N., & Arakkal, F. R. (2011). Spa therapy in dermatology. *Indian Journal of Dermatology, Venereology and Leprology*, 77, 128.

Roychowdhury, P., Aftabuddin, M., & Pati, M. K. (2019). Studies on biochemical responses of table sized *Labeo rohita* (Hamilton, 1822) to the thermal exposure at critical maximum temperature (CTmax). *Exploratory Animal and Medical Research*, 9(2), 197-203.

Roychowdhury, P., Aftabuddin, M., & Pati, M. K. (2020a). Thermal stress–induced oxidative damages in the liver and associated death in fish, *Labeo rohita. Fish Physiology and Biochemistry*, 1-12.

Roychowdhury, P., Aftabuddin, M., & Pati, M. K. (2020b). Thermal stress altered growth performance and metabolism and induced anaemia and liver disorder in *Labeo rohita. Aquaculture Research*, 51(4), 1406-1414.

Ruane, N. M., Huisman, E. A., & Komen, J. (2001). Plasma cortisol and metabolite level profiles in two isogenic strains of common carp during confinement. *Journal of Fish Biology*, 59(1), 1-12.

Salinthone, S., Tyagi, M., & Gerthoffer, W. T. (2008). Small heat shock proteins in smooth muscle. *Pharmacology & Therapeutics*, 119(1), 44-54.

Sapolsky, R. M. (1996). Stress, glucocorticoids, and damage to the nervous system: the current state of confusion. *Stress*, 1(1), 1-19.

Schlesinger, M. J. (1990). Heat shock proteins. *Journal of Biological Chemistry*, 265(21), 12111-12114.

Schreck, C. B., Contreras-Sanchez, W., & Fitzpatrick, M. S. (2001). Effects of stress on fish reproduction, gamete quality, and progeny. *In Reproductive Biotechnology in Finfish Aquaculture* (pp. 3-24).

Selye, H. (1936). A syndrome produced by diverse nocuous agents. *Nature*, 138(3479), 32-32.

Shi, Y. A. N. G. G. U., & Thomas, J. O. (1992). The transport of proteins into the nucleus requires the 70-kilodalton heat shock protein or its cytosolic cognate. *Molecular and Cellular Biology*, 12(5), 2186-2192.

Sorte, C. J., Jones, S. J., & Miller, L. P. (2011). Geographic variation in temperature tolerance as an indicator of potential population responses to climate change. *Journal of Experimental Marine Biology and Ecology*, 400(1-2), 209-217.

Tacon, A. G., & Metian, M. (2008). Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. *Aquaculture*, 285(1-4), 146-158.

Ton, C., Stamatiou, D., & Liew, C. C. (2003). Gene expression profile of zebrafish exposed to hypoxia during development. *Physiological Genomics*, 13(2), 97-106.

Vijayan, M. M., & Moon, T. W. (1994). The stress response and the plasma disappearance of corticosteroid and glucose in a marine teleost, the sea raven. *Canadian Journal of Zoology*, 72(3), 379-386.

Vijayan, M. M., Foster, G. D., & Moon, T. W. (1993). Effects of cortisol on hepatic carbohydrate metabolism and responsiveness to hormones in the sea raven, *Hemitripterus americanus. Fish Physiology and Biochemistry*, 12(4), 327-335.

Vijayan, M. M., Mommsen, T. P., Glémet, H. C., & Moon, T. W. (1996). Metabolic effects of cortisol treatment in a marine teleost, the sea raven. *Journal of Experimental Biology*, 199(7), 1509-1514.

Vijayan, M. M., Pereira, C., Grau, E. G., & Iwama, G. K. (1997). Metabolic responses associated with confinement stress in tilapia: the role of cortisol. *Comparative Biochemistry and Physiology Part C: Pharmacology, Toxicology and Endocrinology*, 116(1), 89-95.

Volpato, G. L., & Barreto, R. E. (2001). Environmental blue light prevents stress in the fish Nile tilapia. *Brazilian Journal of Medical and Biological Research*, 34(8), 1041-1045.

Wang, J., Wei, Y., Li, X., Cao, H., Xu, M., & Dai, J. (2007). The identification of heat shock protein genes in goldfish (Carassius auratus) and their expression in a complex environment in Gaobeidian Lake, Beijing, China. *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology*, 145(3), 350-362.

Wedemeyer, G. A. (1997). Effects of rearing conditions on the health and physiological quality of fish in intensive culture. *Fish Stress and Health In Aquaculture*, 35-71.

Wendelaar Bonga, S. E. (1997). The stress response in fish. *Physiological Reviews*, 77(3), 591- 625.

Weyts, F. A. A., Cohen, N., Flik, G., & Verburg-van Kemenade, B. M. L. (1999). Interactions between the immune system and the hypothalamo-pituitary-interrenal axis in fish. *Fish & Shellfish Immunology*, 9(1), 1-20.

Wodemeyer, G. A., & McLeay, D. J. (1981). Methods for determining the tolerance of fishes to environmental stressors. *In Stress and fish* (pp. 247-275). Academic Press, Western Fisheries Research Center.

Wu, C. (1995). Heat shock transcription factors: structure and regulation. *Annual Review of Cell and Developmental Biology*, 11(1), 441-469.

Xing, T., Gao, F., Tume, R. K., Zhou, G., & Xu, X. (2019). Stress effects on meat quality: A mechanistic perspective. *Comprehensive Reviews in Food Science and Food Safety*, 18(2), 380-401.