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Review

An overview of climate-driven stress responses in striped catfish (*Pangasianodon hypophthalmus*) – prospects in aquaculture

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Abstract: Aquaculture sector significantly contribute in terms of food and nutrition security, sustainable livelihood, poverty eradication as well as overall economic development throughout the world. However, sustainable aquaculture production is a great challenge due to the climate change issues including global warming, rainfall variation, flood, and salinity intrusion. To consider the negative effects of climate changes on aquaculture production, culture of striped catfish can be one of the effective strategies for adaptation to climate changes. The capability to tolerate several adverse environmental conditions makes it a suitable aquaculture species. Moreover, striped catfish can be cultured at high stocking densities in wide range of waterbodies such freshwater, brackish water and saltwater environment as well as culture practices including monoculture, polyculture, and cage culture. Finally, it is highly recommended that striped catfish could be the best suitable candidate for aquaculture to adapt the future climate changes.

Keywords: aquaculture; environment; global warming; pangasius; pollution; salinity

1. Introduction

Aquaculture, the most prominent and unique sector that generates animal protein all over the world (Belton and Thilsted, 2014). This sector has become a reliable support that continuously trying to ensure safe food and nutrition for people in different parts of the world (Chan *et al.*, 2019; Dawood *et al.*, 2020). Moreover, aquaculture industry plays a significant role in livelihood, poverty reduction as well as economic growth for millions of people with its associated activities like fish seed production and supply, fish feed and aqua-drugs industries, transportation sector, marketing etc. (Kumar and Engle, 2016; Gomes Ferreira *et al.*, 2020; Teodósio *et al.*, 2020). Aquaculture production is rapidly increasing and it accounts 82.1 million tons (46%) in 2018 where Asia contributes the major part (FAO, 2020). However, it is expected that the rapid growth of this sector will enhance the world fish production from 46% to 53% within 2030 (FAO, 2020). However, despite the huge development sustainability of this sector is a serious concern due to the climate change. Simply, climate change is the variation from normal range of weather that exists from decades to millions of year over a long period of time (Yazdi and Shakouri, 2010). Climate change is the cumulative results of various human activities including deterioration of fossil fuels like coal, oil, gas (Gao *et al*., 2016; Palmer and Stevens, 2019) and destruction of forest (Abouelfadl, 2012; Khaine and Woo, 2015). Climate change acts as a major obstacle that drastically hampers the global food production both qualitatively as well as quantitatively (Beach and Viator, 2008; Hamdan and Kari, 2015; Myers *et al.*, 2017) and is a serious threat to food security (Kandu *et al*., 2017). Several studies reported that several alterations in climate such as temperature rise, salinity intrusion, heavy metals and pesticides pollution have negatively affected the sustainable aquaculture production (Ateeq *et al*., 2006; Cao *et al*., 2009; Huang *et al*., 2010; Hussain *et al*., 2012; Zhang *et al*., 2012; Blanchard *et al*., 2017; Troell *et al*., 2017; Dabbadie *et al*., 2018) and hence, entire cycle of aquaculture production will be in a very vulnerable situation (Fleming *et al.*, 2014). Climate change directly affect the different physiological aspect of finfish as well as shellfish while indirectly it has huge impact on overall production, ecosystem pattern, prices of several necessary inputs regarding aquaculture activities (De Silva and Soto, 2009; Freeman, 2017; Adhikari *et al.*, 2018). In order to accept such challenges, a conjugal effort both from the industry as well as communities' level will play an effective role to mitigate and adapt new technologies by using alternative resources. And such mitigation and adaptation will be an effective and efficient strategy to resilient such climate changes that reduce or reverse the impacts of climate changes (De Silva and Soto, 2009).

Among various fish species, striped catfish, *Pangasianodon hypophthalmus* is one of the most cultured fish species that significantly contribute to enhance the overall aquaculture production (Hoque *et al.,* 2021). The production of this species greatly contributed the expansion of the world aquaculture over the last 15 years. Although originated from Vietnam, this species has successfully cultured other tropical countries like Thailand, Bangladesh, Myanmar, Cambodia, Indonesia, Malaysia, India and Philippines. It has a tremendous growth rates among the freshwater species in aquaculture (Jeyakumari *et al.*, 2016) and popularly traded around 100 countries due to its skinless and boneless fillet characteristics (Tong Thi *et al.*, 2013). Moreover, it has high market demand as well as consumer preferences due to its favorable characteristics such as white muscle, firm cooked textures and high nutritional status (Rao *et al*., 2013). To consider such negative effects of climate changes on aquaculture, culture of striped catfish can be an effective adaptation option (Anh *et al*., 2016; Mai, 2016) as the fish is capable to grow in freshwater, brackish water and saltwater bodies (Nguyen *et al.*, 2014; Jahan *et al.*, 2019). This review is designed to focus the adaptation capacity of striped catfish aquaculture to climate changes with its culture techniques, global contribution as well as physiological responses to climate changes.

2. Global contribution of striped catfish

The striped catfish has been recognized as a superior aquaculture species for tropical regions throughout Southern Asia. Not only in Southern Asia but also striped catfish being cultured in North American countries like the Dominican, Haiti, Costa Rica, Puerto Rico, Jamaica, etc., and Oceanian country Vanuatu. Germany is the only European country that started the culture of this fish in 2019. India, Bangladesh, Indonesia and Myanmar are the leading producer of striped catfish worldwide after Vietnam. Globally, India produces 0.61 million MT of striped catfish and is the second largest producer after Vietnam (1.5 million MT) and then Bangladesh comes in the third position with a total production of 0.40 million MT (Figure 1a). Thailand and Malaysia have also contributed greatly to striped catfish production. However global production appears to be tapering off at around 2.5 million tons, market research indicates continued increasing demand for striped catfish. Growth in the production of striped catfish had been dramatic in recent years with total global production of little over 2.5 million tons in 2020 which was 5.1% of fish aquaculture (Figure 1b). Moreover, as a commercial aquaculture species, striped catfish attains values nearby those of other species widely farmed, such as salmon, tilapia, and other carp species in world markets.

Despite being the most consumable aquaculture species in Asia, striped catfish has been known to consumers in international markets as an affordable, healthy choice. It is catering to mass market as white fish in the Western palate/taste. Recently, striped catfish has evolved into a global product, sold to the markets of the US, Europe and throughout the Asia-Pacific. The striped catfish was exported to around 150 countries worldwide at a value close to USD 2 billion. The production of striped catfish fillets complies with strict food safety standards attracts the consumers worldwide. Therefore, all major supermarket chains in international markets have striped catfish fillets in the assortment. Around 3.1 million tons of the whole striped catfish will be produced around the world by the end of 2022 and moreover, the striped catfish industry is expected to produce about 1.6-1.7 million tons of commercial striped catfish; striped catfish export turnover reached over 1.6 billion USD. Even though the striped catfish has achieved remarkable success in Asia, tropical areas of the Western Hemisphere have not generally adopted it as a culture species. Still Latin America is the largest and fastest-growing market to import striped catfish products.

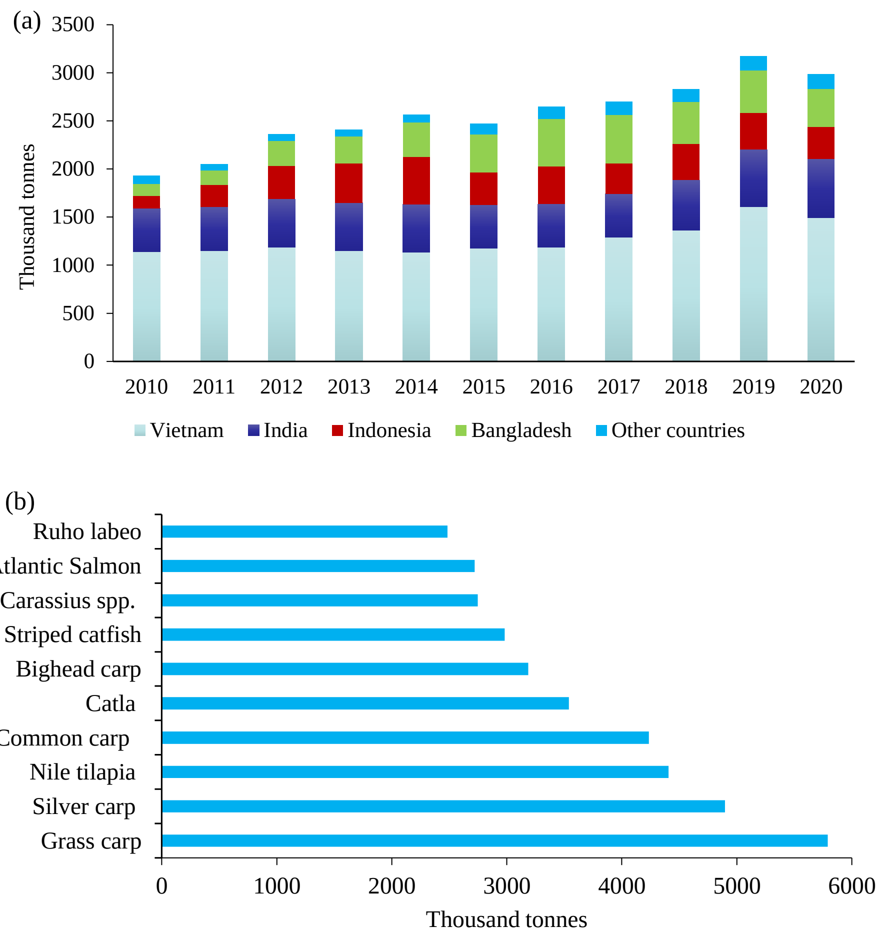

Figure 1. (a) Global production of striped catfish during 2010 – 2020, and (b) Worldwide production of major aquaculture species in 2020 (FAO, 2022).

3. Culture system of striped catfish

Initially, the striped catfish was captured, particularly in Vietnam in the 1940s and, to a lesser extent, in Thailand and Cambodia. Then it was discovered that striped catfish is raised in high stocking densities, has a quick growth rate, and high feed efficiency. Aquaculture has thus gradually replaced fish catch over time, and it is now a significant aquaculture species in Bangladesh, Cambodia, China, Indonesia, Malaysia, and the Lao People's Democratic Republic. Large-scale striped catfish farming systems in the Mekong Delta are increasingly replacing intensive small-scale striped catfish farming systems to meet future demands for income, food security, and increased gross domestic product (De Silva and Phuong, 2011). The months when pangas are grown are from March to December, while some breeding process taken places in March to June, and some sometimes cryopreserved milt usually used (Hossain *et al*., 2016). In Bangladesh, the practices of induced breeding and brood stock management for Pangas are upheld with a focus on high-quality standards, driven by the excellent profitability and abundant yields they offer (Shabuj *et al*., 2016; Ali *et al*., 2016 a, b). Intensive and semi-intensive farmers start harvesting fish after three months and continue doing so at regular intervals throughout the rest of the year, even though the majority of farmers stock their ponds from March to May. There have been different culture systems for striped catfish like monoculture, polyculture, cage culture, pen culture, rice-fish farming as well as modern technologies such as recirculating aquaculture systems (RAS) and biofloc system being practiced around the world.

3.1. Inland freshwater aquaculture

In Vietnam, striped catfish production was initiated with polyculture in semi-intensive earthen ponds before 1975, later intensive farming started in late 1990s in wooden cages and net fences and today with progressive development of this sector culture system has been upgraded to more intensive RAS system. Thailand was the origin of the concept of monoculture for striped catfish, which is still widely used in Southeast Asian nations like Vietnam, Thailand, and the Philippines (Ahmed, 2013; Belton and Thilsted, 2014). Striped catfish have a higher growth rate and feed utilization (Sarkar *et al*., 2016). The major problem in monoculture system was the excessive growth of plankton, remaining unutilized plankton used to cause algal blooms, which led to many unintended problems, such as a decline in dissolved oxygen. For that, polyculture approach was adopted to avoid all these problems (Sarkar *et al*., 2006; Anka *et al*., 2013; Podduturi *et al*., 2017). Although striped catfish farmers in Bangladesh began with a monoculture, similar to Vietnam, they later switched to a polyculture with both native and exotic carps. Striped catfish can be produced under polyculture in extensive, semi-intensive and intensive farming systems and therefore, polyculture system can be a profitable business where feeding, stocking density, and species composition are major influential factors to facilitate a sustainable increase in fish production (Islam *et al*., 2008; Ali *et al*., 2014). In Vietnam, polyculture or composite culture in earthen ponds has long been a traditional practice. In reality, it is a system in which fast-growing compatible species with different feeding habits are stocked in different proportions in the same ponds to avoid food competition and best utilize natural foods with different feeding habits without harming each other (Jhingran, 1975). While larger specimens also consume fruit, crustaceans, and fish, striped catfish are omnivorous and eat algae, higher plants, zooplankton, and insects (FAO, 2020). Hence, striped catfish –carp polyculture is adopted by fish farmers to increase pond productivity by utilizing the unused food particles in striped catfish pond because a substantial amount of artificial feed is added to the culture system, with approximately 5-28% of it still present unutilized which results in phytoplankton production and catla as a fast-growing fish, feeds on phytoplankton in the upper layer of the pond avoiding competition with striped catfish for artificial feed (Bais, 2018). For instance, striped catfish polyculture with carps was successful in the semi-intensive culture at a ratio of 30:70 as well as the proportion of 1:1 of striped catfish and silver carp, which maintained acceptable growth performance and survival of both species, as well as economic benefit (Sarkar and Khan, 2006; Khan *et al.*, 2009). This is because planktivorous silver carp *Hypophthalmichthys molitrix* has been reported to be stocked in aquaculture ponds to manage phytoplankton bloom in different countries (Barry, 1983) for proper utilization of phytoplankton and maintenance of water quality. Additionally, when fed higher levels of crude protein (32% for fry and 28% for adults), striped catfish and rohu (*Labeo rohita*) showed a typical increasing trend of higher growth, with the striped catfish (872 g) having the highest SGR (Sayeed *et al.*, 2008). Additionally, striped catfish production in polyculture with freshwater prawn and carps, reached 5.88 tons per hectare, and was more profitable than striped catfish production in monoculture (Islam *et al.*, 2008). On the contrary, striped catfish exhibited a better growth performance, feed utilization and survival in polyculture with low Nile tilapia proportion (Mansour *et al*., 2021), as higher proportion both the species may compete for food both have the same feeding habit. Even though striped catfish are scavengers, they are not mandatory predators, even at larger sizes, as no notable predation occurred when they were polycultured with freshwater prawns (*Macrobrachium rosenbergii*). However, polyculture of striped catfish using freshwater giant prawn (*Macrobrachium rosenbergii*) and carps catla and rohu (*Labeo rohita*) at stocking density 10,000, 2500, 5000, and 3750 respectively ha^{-1} of using inexpensively formulated feed can be even more economical in terms of fish yield per unit area, feed utilization, and ecological balance than monoculture (Islam *et al.*, 2008).

Since the middle of the 19th century, the native riverine striped catfish has been raised on a limited scale in pens and ponds in Central Thailand. In the past, catfish farming in cages and pens was also conducted in Vietnam (Nguyen, 2009). Because *Pangasius conchophilus* can endure a wide variety of environmental conditions, this species can be cultured in cages at high stocking densities without suffering any negative effects on mortality. Therefore, raising striped catfish in cages in Bangladesh's floodplains at high stocking densities and short harvest intervals could be a viable alternative for the area's small-scale fish producers (Jiwyam, 2011; Chowdhury and Roy, 2020).

An integrated aquaculture with rice and vegetable crop farming system has also been adopted where farmers are using wastewater and sludge from striped catfish (stocking density of 30 fish/m^2) ponds to increase the crop yield and thus generate a higher net profit *(*Thanh *et al.* 2014; Da *et al.*, 2015; Thi *et al.*, 2017). RAS have been used to produce striped catfish in response to environmental regulations, reducing waste discharge and improving water quality in fish ponds. These efforts will eventually contribute to a decrease in the occurrence of fish diseases, resulting in decreased mortality and a decrease in the need for medication (Martins *et al.,* 2010; Rijn, 2013). The economic viability of RAS in striped catfish farming revealed that for large farms, net present value increases from an average of 589,000 to 916,000 USD/ha after implementing RAS in striped catfish farming, where the key factors determining profitability are price, yield, costs of fingerling, feed, and initial investment. To increase the sustainability of striped catfish production, these findings on the stability of RAS's economic performance are helpful (Ngoc *et al.,* 2016).

3.2. Coastal/brackish water aquaculture

Though shrimp is the most cultured species in low-lying coastal areas, it is most vulnerable to disease outbreaks. An alternative approach to this problem can be crop diversification, such as polyculture rather than shrimp monoculture, might be an effective component of sustainable aquaculture. Furthermore, the highly vulnerable coastal lands can be exploited through climate adaptive sustainable aquaculture by integrating brackishwater culturable fish species from the diverse trophic level in shrimp monoculture to expand coastal aquaculture production. In this situation, striped catfish may be a viable species in polyculture that can partially offset economic losses caused by the unanticipated death of shrimp in a monoculture system that is highly susceptible to disease outbreaks. At these abandoned facilities, striped catfish and shrimp polyculture may offer a chance to restart a successful and long-lasting aquaculture system. Striped catfish and shrimp barely live in the same habitat in nature but it is well known that species from multiple trophic levels can be cultured together, so they can also be co-cultured together in captive condition.

However, because commercial feed floats while homemade feed sinks, striped catfish can be trained to eat at the surface even though they are naturally bottom feeders (Nguyen *et al.,* 2014). Though in the case of extensive polyculture, shrimp spend most of their time near the pond's bottom, grazing on bacterial films on the bottom substrate and detritus that settles from above as well as striped catfish are also naturally bottom feeders feeding on algae, higher plants, zooplankton and insects. However, almost 97% of striped catfish farms in the Mekong Delta, Vietnam use commercially made feed (Phan *et al.,* 2009) and thus the leftover feed particles getting to the bottom can be utilized by the shrimp. Moreover, both striped catfish and shrimp can intensively be cultured in high stocking densities. Striped catfish are commonly reared at exceedingly high stocking densities of 60-80 fish/m^2 and it can be as high as 120 fish/m^2 (Phan *et al*., 2009). Penaeid shrimp and striped catfish are both euryhaline species. They are also relatively tolerant to crowding and rapid changes in water quality. Therefore, it can be a suitable candidate for expanding its culture to brackish waters, the areas that are severely impacted by global climate change (seawater encroachment, storms etc.).

4. Effects of different environmental parameters on physiology of striped catfish

4.1. Temperature

Temperature is one of the most crucial parameters that significantly influence the production and development of the aquatic species (Ngoan, 2018; Shahjahan *et al.,* 2020; Islam *et al.,* 2020). As being poikilothermic in nature, a tiny variation in temperature caused by climate changes the normal physiological activities of fish (Sae-Lim *et al.,* 2017; Ashaf-Ud-Doulah *et al.,* 2021; Shahjahan *et al.,* 2021b; Islam *et al.,* 2022). Several studies predicted that stress mediated form thermal fluctuations may increase mortalities of several fish species especially cold-water species (Matt Gubbins, 2013). Prolonged thermal stress may hamper the neuroendocrine as well as osmoregulatory functions that negatively affect the cardiorespiratory functions as well as immunity of commercially important aquaculture species (Brodie *et al.,* 2014; Gazeau *et al.,* 2014; Paukert *et al.,* 2016; Stévant *et al.,* 2017; Stewart *et al.,* 2019; Zhang *et al.,* 2019). Moreover, metabolic activity, feeding responses, growth performances, behavior, reproduction, energy requirements etc. of several finfish and shellfish species seriously affected by thermal alterations (Marcogliese, 2008; Akegbejo-Samsons, 2009; Maulvault *et al.,* 2017; Chang *et al.,* 2018; Lemasson *et al.,* 2019). And such modification in physiology like homeostasis, osmotic and ionic control of fish due to extreme temperature raise causes mass fish mortality (Madeira *et al.,* 2016; Shrivastava *et al.,* 2017; Shen *et al.,* 2018). Moreover, extreme temperatures caused several abnormalities (karyopyknosis, nuclear bridge, notched, nuclear bud) and (tear-drop, twin, elongated, spindle shaped) in nucleus and cell of the fish erythrocytes (Figure 2) (Shahjahan *et al.,* 2018; Islam *et al.,* 2019; Shahjahan *et al.,* 2022). In this scenario, measures like adaptations, acclimatization against such thermal alterations can be very effective for the survival of fish (Rahman *et al.,* 2021). It is generally assumed that the species having more adaptation capacity distributed widely. The distribution of striped catfish throughout the world assures this assumption. The effects of thermal changes on several physiological aspects of striped catfish are summarized in Table 1. It has been reported that elevated temperatures (27–33°C) did not significantly affect the growth and feed utilization of *P. hypophthalmus* (Huong *et al.,* 2021). Increased temperature (36°C) resulted higher blood glucose level while lower the hemoglobin and dissolved oxygen level which confirmed the stressful condition of striped catfish (Shahjahan *et al.,* 2018; Islam *et al.,* 2019). *P. hypophthalmus* exhibited best performances at 32°C (Islam *et al.* 2019) while (De Silva and Phuong, 2011) observed up to 34°C considered as the best thermal conditions. (Ranjan *et al.,* 2020) revealed that there was no negative effect of higher temperature (32°C) on the growth and nutrient utilization of striped catfish in comparison with the ambient temperature (24.5°C). Erythrocyte methaemoglobin (metHb) reductase activity increased with the temperature increase that efficiently reduce metHb to functional Hb (Ha *et al.,* 2019). Although gill respiratory surface area and blood barrier thickness were affected by higher temperature (33°C), growth rate was around 8-fold faster than the lower temperature (27°C) group (Ha *et al.*, 2019). Moreover, striped catfish were able to adapt themselves in temperatures changes through increasing their RBC and Hb level (Phuc *et al.*, 2017). Islam *et al.* (2019) reported that the species exhibited the best growth performances up to 32°C while extreme high (36°C) and extreme low (24°C) temperatures become very stressful. So, from these discussions it is clear that striped catfish able to cope up with high temperatures and can be a suitable candidate to introduce in climate smart aquaculture production systems.

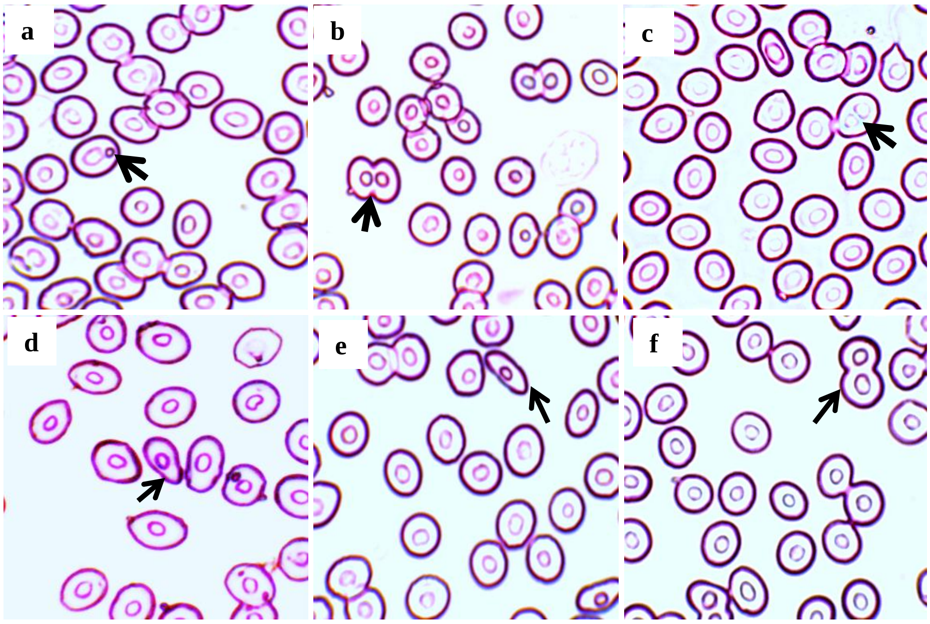

Figure 2. Nuclear (a, b & c) and cellular (d, e & f) abnormalities in Giemsa-stained blood smears of striped catfish exposed to high temperature (Shahjahan *et al*., 2018; Islam *et al*., 2019), salinity (Jahan *et al*., 2019), and heavy metals (Islam *et al*., 2020; Akter *et al*., 2021; Suchana *et al*., 2021); (a) micronucleus, (b) nuclear bridge, (c) binuclear, (d) tear-drop, (e) elongated and (f) twin.

Table 1. Effects of temperature exposure on physiological responses in striped catfish *Pangasionodon hypophthalmus*.

Stages	Temperature	Exposure time (Days)	Effects	References
Juvenile	27, 30, & 33°C	3	increased glucose and cortisol levels	Huong *et al*. (2021)
Juvenile	24.5 & 32°C	60	increased AST & ALT activity, and decreased liver tissue as temperature increased	Ranjan *et al*. (2020)
Juvenile	25, 30 & 35°C	1.5	decreased TCS with the increase in temperature	Paul *et al*. (2020)
Fingerling	25, 28, 31 & 35°C	10	highest bio-film formation at 25°C & extreme reduced biofilm at 35°C	Nguyen *et al*. (2020)
Adult	38°C	84	degeneration (minor) of gonad	Majhi *et al*. (2019)
Fingerling	26.2-34.2°C	4	higher catalase, SOD and GST, altered blood glucose, NBT, LDH, & MDH	Kumar *et al*. (2019)
Fingerling	27°C & 33°C	7	higher blood [nitrite] and metHb contents at 27°C, increased erythrocyte metHb reductase activity	Ha *et al*. (2019)
Fingerling	24, 28, 32 & 36°C	28	increased WBC, glucose; decreased Hb, RBC; increased frequencies of ECA & ENA	Islam *et al*. (2019)
Fingerling	25, 30 & 35°C	30	decreased TEC, Hb, PCV, MCH, MCV, increased TLC, MCHC and RDW, activity of LDH, SOD, CAT, and GST in liver and AChE at 35°C	Paul *et al*. (2019)

Table 1. Contd.

Stages	Temperature	Exposure time (Days)	Effects	References
Unidentified	45, 50, & 50°C	Not declared	Decreased ash content at high temperature, Decreased protein with increased temperature	Pradarameswari *et al*. (2018)
Fingerling	34°C	4	higher activities showed by liver, gill and brain; higher AST activities in different organs, alterations cellular and metabolic activities	Kumar *et al*. (2018b)
Fingerling	28, 32, & 36°C	7	increased WBC & Blood glucose, decreased Hb & RBC	Shahjahan *et al*. (2018)
Juvenile	24.5 & 32°C	60	higher growth performance and nutrient efficiency	Ranjan *et al*. (2018)
Juvenile	27 & 33°C	42	affected gill respiratory surface area and blood barrier thicknesses	Phuong *et al*. (2017)
Juvenile	25, 30, & 35°C	14	affected WG at 35°C, increased Hb & RBC at 35°C	Phuc *et al*. (2017)
Fingerling	25 & 35°C	Several months	decreased Hb and blood at higher temperatures	Damsgaard *et al*. (2015)
Juvenile	28°C to 15°C	1	decreased mortality in cold challenged fish, no differences in cortisol and glucose levels	Soltanian *et al*. (2014)
Embryo	23 to 33°C	-	lower size heterogeneity and higher survival at optimum temperature	Baras *et al*. (2011)
Larval	30, 34 & 38°C	30	Increased O_2 consumption in 30-34°C	Debnath *et al*. (2006)

AChE; acetylcholinesterase, AST; aspartate aminotransferase, ALT; alanine aminotransferase, CAT; chloramphenicol acetyltransferase, ECA; erythrocytic nuclear abnormalities, ENA; erythrocytic nuclear abnormalities, GSI; gonadosomatic index, GST; glutathione s-transferase, Hb; hemoglobin, LDH; lactate dehydrogenase, MCH; mean corpuscular hemoglobin, MCHC; mean corpuscular hemoglobin concentration, NBT; nitroblue tetrazolium, PCV; packed cell volume, RBC; red blood cell, RDW; Red cell distribution width, PER; protein efficiency ratio, SGR; specific growth rate, SOD; Superoxide dismutase, TEC; transient erythroblastopenia of childhood, WBC; white blood cell and WG; weight gain.

4.2. Salinity

Climate change resulted increase of level of salinity in the coastal areas which has become a major concern for the tropical and subtropical countries. This raise of salinity level not only affect the fertility of the coastal areas (Islam *et al.,* 2005) but also altered the physicochemical parameters of the aquatic waterbodies that negatively affect the associated flora and fauna (Ahmed, 2013). And these variations in salinity level may be occurred due various types of changes in climate including rising temperatures, ocean circulation changes (Robinson, 2005). These variations significantly affect the ocean's capability of storing heat, carbon and nutrient circulation and such type of changes negatively affect the environmental sustainability of aquaculture by reducing production, increasing mortalities, lowering the performances of immune systems (Baker *et al.,* 2005, 2007; Rodrick, 2008; Ahmed, 2013; Morash and Alter, 2016; Nguyen *et al.*, 2018). Every aquatic species have their optimum salinity levels and deviation from this may cause huge production loss as well as mortalities (Maulu *et al.,* 2021). However, cultivation of salinity tolerant species can be very useful to adapt such changes (Jahan *et al.*, 2019). Striped catfish tolerate salinity up to 8‰ without averting growth and hemato-biochemical parameters and hence therefore, recommended as a suitable species to culture in brackish water (Jahan *et al.*, 2019). Salinity derived stress caused several abnormalities in nucleus (karyopyknosis, nuclear bridge, notched, nuclear bud) and cell (tear-drop, twin, elongated, spindle shaped) of striped catfish's erythrocytes (Figure 2) (Jahan *et al.*, 2019). Moreover, exposure to high salinities caused several histopathological alterations (Figure 3) in gills, liver and kidney of fish (Hossain *et al.,* 2022). The effects of salinity changes on several physiological aspects of striped catfish are summarized in Table 2. It has been evaluated the impacts of salinity on embryonic and larval development of striped catfish and revealed that no negative impacts were observed on hatching success, larval development and survival rate up to 8 ppt and therefore, recommended the hatchery production of this species to introduce in low saline brackish water (Hossain *et al.*, 2022). Jaapar *et al.* (2021) reported that salinity has no positive impact on hatching and survival of *Pangasius nasutus*, however 1 ppt suggested for hatching activities and larval rearing. Eggs of matured Thai Pangas (*Pangasius hypophthalmus*) treated with formalin suggested that high fertilization and hatching rate of eggs, survival and growth performance of fry (Rahman *et al*., 2019). Microbial scenario of striped catfish's intestine significantly influenced by environmental salinity and no significant disruption of intestinal micro-biota were observed up to 10‰ (Hieu *et al*., 2022). However, (Hieu *et al*., 2022) suggested that modifications of expression of genes in intestine associated in ion exchange and stress response can be very effective to introduce this fish species in hyperosmotic environment. Larvae of striped catfish performed normal in terms of growth and survival rate up to 10 ppt while increase salinity than that resulted very stressful condition (Hieu *et al*., 2021). Though growth and feed utilization negatively correlated with the increase of salinity above 4ppt while no negative impacts were observed on survival rate of pangas up to 12 ppt (Mandal *et al*., 2020). Striped catfish were able to adapt themselves in salinity alterations by enhancing their RBC and Hb levels in blood and hence, showed best growth performance with superior feed utilization at salinity level up to 6‰ (Phuc *et al*., 2017). Performance of striped catfish quite very well up to 10 ppt (Ali *et al*., 2014; Nguyen *et al*., 2014) and 9 ppt (Thanh *et al*., 2014) without compromising the growth performance. From these findings we can conclude that striped catfish could be very much adaptable to climate change mediated salinity intrusion and a suitable candidate to culture in low saline brackish water.

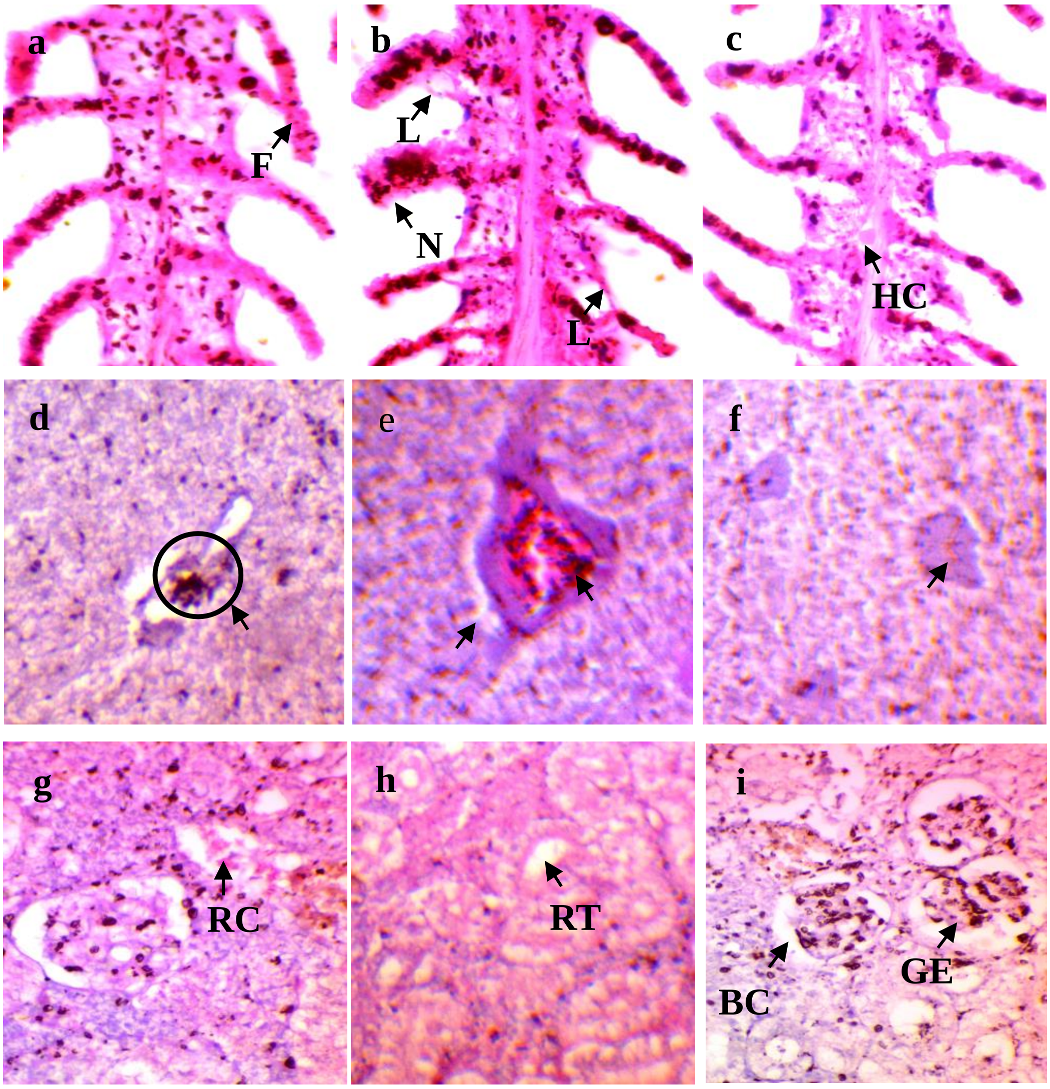

Figure 3. Histo-pathological changes in gills (a, b & c), liver (d, e & f) and kidney (g, h & i) of striped catfish exposed to salinity (Hossain *et al*., 2022), and heavy metals (Islam *et al*., 2020; Suchana *et al*., 2021); a. clubbed lamella, necrotic lamellae, c. hypertrophy of chloride cells, b. lamellar fusion, d. melano-macrophage centers, e. blood congestion, f. hemorrhage, g. shrinkage of renal corpuscle; h. increasing in the diameter of renal tubules, and i. glomerular expansion, dilation of bowman's space.

Table 2. Effects of salinity exposure on physiological responses in striped catfish *Pangasianodon hypophthalmus*.

Stages	Concentrations (ppt)	Duration (days)	Effects	References
Juveniles	0, 5, 10, 15 & 20 psu	34	disturbed gut microbiome at 10 psu	Hieu *et al*. (2022)
Fingerlings	0, 4, 8 & 12	56	increased histological anomalies in gills, liver and kidney at 8 & 12 ppt	Hossain *et al.* (2022)
Juvenile	0, 5, 10, 15 & 20 psu	10	highest survival at 5 psu all fish perished at 15 psu	Hieu *et al*. (2021)
Embryo and larvae	0, 2, 4, 6, 8, 10 & 12	-	reduced hatching rate at 8 &10 ppt, increased developmental deformities at 10 ppt	Hossain *et al.* (2021)
Embryo and larvae	0, 1, 2 & 3	30	no effect on the rate of survival and hatching	Jaapar *et al*. (2021)
Fingerling	0, 2, 4, 6, 8, 10, 12, 14 & 20	60	no change in FCR at 20 ppt but all fish perished	Mandal *et al.* (2020)
Fingerling	0, 4, 8 & 12	56	Increased WG, SGR at 4 ppt, decreased Hb and RBC at 8 &12 ppt, increased WBC and glucose at 8 &12 ppt, increased frequency of ENA and ECA at 8 &12 ppt	Jahan *et al.* (2019)
Juveniles	0, 6, & 12	56	best growth at 6 ppt, increased glucose at 12 ppt, lowered Hct at 12 ppt, higher osmotic pressure at 12 ppt	Phuc *et al*. (2017)
Fingerlings	0 & 15	56	exhibited predictable plastic regulatory responses to elevated salinity	Nguyen *et al.* (2016)
Juveniles	0, 2, 6, 10, 14 & 18	56	no negative effects on WG, SGR, FCR up to 10 ppt	Nguyen *et al.* (2014)
Fingerlings	0, 6, 9, 12 & 15	42	best growth at 9 ppt	Thanh *et al.* (2014)
Fingerlings	0-0.5, 5-7 & 10-12	160	higher production at 10 ppt	Ali *et al.* (2014)

ECA; erythrocytic nuclear abnormalities, ENA; erythrocytic nuclear abnormalities, FCR; feed conversion ratio, Hb; hemoglobin, Hct; hematocrit, ppt; Parts per thousand, RBC; red blood cell, SGR; specific growth rate, WBC; white blood cell, WG; weight gain

4.3. Heavy metals

Heavy metals contamination has been considered a serious threat to the aquatic ecosystems and imparts several hazardous impacts on associated floral and faunal communities (Sarkar *et al.,* 2016; Islam *et al.,* 2020; Suchana *et al.,* 2021; Taslima *et al.,* 2022). However, several metals acts as an important micro-minerals in fish feed (Akter *et al.*, 2021) but excess level than the recommendation caused very harmful. Several studies reported that toxicities derived from heavy metals resulted various complexities in different stages of fish including reproductive failure, huge mortalities, unusual heart rate, cardiac arrest, irregular shape etc. (Cao *et al.,* 2009; Huang *et al.,* 2010; Zhang *et al.,* 2012; Witeska *et al.,* 2014; Łuszczek-Trojnar *et al.,* 2014; Santos *et al.,* 2018; Gárriz *et al.,* 2019; Yan *et al.,* 2020). The effects of heavy metals on several physiological aspects of striped catfish are summarized in Table 3. Though Cr supplementation up to 4 mg/kg improved the growth and feed utilization of striped catfish (Akter *et al., 2021*) but excess level resulted various detrimental effects including various types of erythrocytic cellular as well as nuclear abnormalities (Figure 2) (Islam *et al.,* 2020; Suchana *et al.,* 2021). Cr toxicity seriously affects the normal activities through damaging several important organs including gills, liver and kidney of fish (Figure 3) that ultimately hampers the production (Suchana *et al.,* 2021). Moreover several studies reported that toxic effects of several metals interrupts the respiratory functions, causes hepatic dysfunctions, malfunctions of germ cells as well as interstitial tissues of striped catfish (Yamaguchi *et al.,* 2007; Priya *et al.,* 2012; Neeraj Kumar *et al.,* 2017; Kumar *et al.,* 2018; Mahmuda *et al.,* 2020). On the other hand, several metals including Cr (Akter *et al.,* 2021), As (Neeraj Kumar, 2021), and Se (Neeraj Kumar *et al.,* 2020) significantly improve the growth, feed utilization of striped catfish.

Table 3. Effects of heavy metals exposure on physiological responses in striped catfish *Pangasionodon hypophthalmus*.

Stages	Heavy metals	Doses	Exposure time (days)	Effects	Reference
Fingerling	Cr	0.8, 1.6, and 3.2 mg/L	30	decreased Hb and RBC, increased blood glucose and WBC, decreased DNA in blood and tissues of different vital organs	Suchana *et al.* (2021)
Fingerling	Cr	0, 2, 4, and 8 mg/kg	60	increased WG, %WG, and SGR, and FE and PER, decreased Hb, RBC and blood glucose	Akter *et al.* (2021)
Juvenile	As	2.68 mg/L	90	improved total immunoglobulin, increased glucose and HSP70	Kumar (2021)
Juvenile	Se-NPs	0, 0.5, 1, and 2 mg/kg	60	increased SGR & PER, higher catalase & glutathione peroxidase, lowered malondialdehyde level	El-Sharawy *et al.* (2021)
Fingerling	As, Se-NPs, RF	2.68 mg/L Se-NPs (0 mg kg^{-1}) + RF (0 mg kg^{-1}); Se-NPs (0.5 mg kg^{-1}) + RF (5 mg kg^{-1}); Se-NPs (0.5 mg kg^{-1}) + RF (10 mg kg^{-1}); and Se-NPs (0.5 mg kg^{-1}) + RF (15 mg kg^{-1})	90	increased NBT, total immunoglobulin, myeloperoxidase and globulin reduced albumin and albumin globulin reduced serum cortisol	Kumar *et al.* (2020)
Fingerling	Cr	0, 10, 20, 30, 40, 50 and 60 mg/L	4	decreased RBC & PCV, increased WBC, MCV, & MCH, increased frequencies of ECA & ENA	Islam *et al.* (2020)
Adult	Hg	0.5 ppm, 1 ppm	4	distempered respiratory, loss of balance, showed hepatic cirrhosis	Datta *et al.* (2018)
Fingerling	Pb	4 ppm	60	decreased level of lipid peroxidation, increased AChE	Kumar *et al.* (2018a)
Fingerling	Pb, Se	4 ppm	72	reduced CTmin, LTmin and increased CTmax, LTmax, improved oxidative and metabolic enzymes	Kumar *et al.* (2017)
Adult	Cd, Cr, Pb, Zn	1 ppm, 2 ppm	10	decreased levels of enzymes in liver but increased in muscle	Priya *et al.* (2012)
Adult	Pb Mo Rb As	10^{-7}M 10^{-5} & 10^{-4}M 10^{-5}–10^{-3}M 10^{-5}M	a short period	decreased GSI, caused necrosis of germ cells and large interstitial tissue	Yamaguchi *et al.* (2007)

AChE; acetylcholinesterase, CT; critical thermal, ECA; erythrocytic nuclear abnormalities, ENA; erythrocytic nuclear abnormalities GSI; gonadosomatic index, Hb; hemoglobin, HSP70; heat shock protein 70, LT; lethal thermal, MCH; mean corpuscular hemoglobin, MCV; mean corpuscular volume, PCV; packed cell volume, PER; protein efficiency ratio, RBC; red blood cell, SGR; specific growth rate, WG; weight gain, NBT; nitroblue tetrazolium and WBC; white blood cell.

4.4. Pesticides

Various types of insecticides, pesticides, herbicides and fungicides are frequently used in agricultural crop land to protect from the pests and parasites (Ateeq *et al.,* 2006; Hussain *et al.,* 2012; Badruzzaman *et al.,* 2021). Aquatic environment severely contaminated by these chemicals and seriously affected different aspects of physiological, biological as well as developmental processes of fish which caused severe mortality and drastically lowered the production (Hossain *et al.*, 2015, 2016; Shahjahan *et al.*, 2021a). Several studies reported that pesticides toxicity caused various histopathological as well as molecular changes in liver and kidney of animals including fish (de Campos Ventura *et al.,* 2008; Ahmed *et al.*, 2015, 2016; Vargas and Ponce-Canchihuamán, 2017; Selmi *et al.*, 2018; Singh *et al.,* 2018; Özdemir *et al.*, 2018; Rohani, 2023). The effects of pesticides on several physiological aspects of striped catfish are summarized in Table 4. Sumithion toxicity causes formation of micronucleus, reduced RBCs and Hb levels and increased level of blood glucose and WBCs of striped catfish (Islam *et al.,* 2019). Several studies reported that different stages of striped catfish negatively affected by different pesticides including malathion causes breathing problem (Shashikumar *et al.,* 2018), diazinon and deltamethrin destruct the gills, increased blood RBC, Hb levels and affected the immune system (Hedayati and Tarkhani, 2014; Al-Emran *et al.,* 2022), cypermethrin results several histo-pathological changes in gills and liver (Monir *et al.,* 2016), trichlorofon affects the growth hormones (Sinha *et al.,* 2010).

Table 4. Effects of pesticides exposure on physiological responses in striped catfish *Pangasionodon hypophthalmus*.

Stage	Pesticides	Doses	Exposure time (days)	effects	References
Fingerling	Sumithion	0, 3, 4, 5, 6 & 7 mg/L	4	formed MN, decreased RBCs & Hb, increased WBC & glucose level	Islam *et al.* (2019)
Fingerling	Malathion	7.76, 6.45 & 4.46 µL/L	4	frequent gasping and rapid breathing	Shashikumar *et al.* (2018)
Adult	Cypermethrin	0.00, 0.025, 0.050, 0.075 & 0.10 ml/L	4	severe epithelial necrosis & hypertrophy in gills extensive vacuolation of hepatocytes and pyknotic nuclei in liver	Monir *et al.* (2016)
Juvenile	Diazinon Deltamethrin	0.5 & 1.0 ppm 0.015 & 0.020 ppm	7	damaged gills changed immune function increased RBC, Hct, Hb and MCV	Hedayati and Tarkhani (2014)
Juveniles	Trichlorfon	0.01, 0.1, 0.5 mg/L	56	increased HSP70, COI and CYPIB lowered AChE, growth hormone and trypsinogen	Sinha *et al.* (2010)

AChE; acetylcholinesterase, COI; cytochrome c oxidase subunit I, Hb; hemoglobin, Hct; hematocrit, HSP70; heat shock protein 70, MCV; mean corpuscular volume, MN; micronucleus, RBC; red blood cell and WBC; white blood cell.

5. Conclusions

Sustainability in aquaculture sector has become a great challenge due to continuous and rapid changes in different factors of the climate including thermal alterations, salinity intrusion, heavy metals and pesticides pollution. In this situation, farming of striped catfish can be a suitable option as they can easily adapt themselves in thermal fluctuations and salinity changes. Striped catfish can be cultured in both freshwater and brackish water environment. Development of salinity tolerant strain of striped catfish has become an urgent need and for this a comprehensive and strategic planning needed form both public as well as private sectors. Moreover, this species is very suitable for cultivating at high stocking densities in wide range of culture practices namely monoculture, polyculture, cage culture as well as different types of ponds in coastal and brackish water. However, integrated farming of this species could be another adaptation measures to further climate changes. Additionally, striped catfish can be cultured with other brackish water species as it is able to accept low saline brackish water. Finally, a comprehensive and strategic approach from public as well as private sectors is needed to establish appropriate culture strategies of striped catfish for adaptation to climate changes.

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Data availability

The data that support the findings of this study are available on request from the corresponding author.

Conflict of interest
None to declare.

Authors' contribution
Writing-original draft preparation, Md Meftahul Zannat and Md Shahjahan; writing-review and editing, Md Meftahul Zannat, Farzana Hossain, Umme Ohida Rahman and Md Fazle Rohani; project administration, Md Shahjahan; funding acquisition, Md Shahjahan. All authors have read and agreed to the published version of the manuscript.

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