Review

Tilapia Farming in Bangladesh: Adaptation to Climate Change

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Abstract: In Bangladesh, aquaculture is critically important in terms of providing food and nutrition, sustainable livelihoods, income, and export earnings. Nevertheless, aquaculture in Bangladesh has faced recent concerns due to climate change. Aquaculture is vulnerable to a combination of climatic factors, such as global warming, rainfall variation, flood, drought, temperature fluctuation, and salinity change. Considering the vulnerability of fish production to the impacts of climate change, tilapia farming is one of the possible strategies for adaptation to climate change. The positive culture attributes of tilapia are their tolerance to low water levels and poor water quality with rainfall variation, temperature fluctuation, and salinity change. In fact, tilapia farming is possible in a wide range of water environments, including freshwater, brackish water, and saltwater conditions. We suggest that appropriate tilapia culture strategies with institutional support and collaboration with key stakeholders are needed for adaptation to environmental change.

Keywords: tilapia; aquaculture; climate change; environment; adaptation

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1. Introduction

Aquaculture is the world's fastest growing food producing sector, with a mean annual growth rate of 5.3% during 2001–2018 [1]. Global aquaculture production achieved 82.1 million tons in 2018, of which inland freshwater aquaculture reached 51.3 million tons (62%), while coastal brackish water aquaculture and mariculture (aquaculture is generally practiced in three different types of locations and aquatic environments: (1) inland freshwater aquaculture; (2) coastal brackish water aquaculture; and (3) onshore and offshore marine aquaculture) yielded 30.8 million tons (38%) [1]. Asia led world fish production with a contribution of 89% in 2018. Globally, China is positioned first (58% of total production) among fish producing countries, followed by India, Indonesia, Vietnam, Bangladesh, Egypt, Norway, Chile, Myanmar, and Thailand [1].

Bangladesh is recognized one of the world's most suitable countries for aquaculture practices, because of its promising agroclimatic conditions and favorable biophysical resources. A vast area of shallow water with sub-tropical climate provides perfect situations for aquaculture production. In Bangladesh, both fish production and catch were estimated to be 4.38 million tons in the 2018–2019 fiscal year (Bangladeshi fiscal year: 1 July–30 June), of which 2.49 million tons (57%) were yielded from aquaculture, 1.23 million tons (28%) from inland capture fisheries, and 0.66 million tons (15%) from marine fisheries [2]. The major farming practices for aquaculture in Bangladesh are extensive, semi-intensive, and intensive polyculture and/or monoculture of Indian major carp, exotic carp, catfish, prawn, tilapia, and shrimp.

Aquaculture plays a critical role in the economy of Bangladesh, contributing to food, nutrition, sustainable livelihoods, the income of farming households and associated groups, and export earnings. Fish accounts for 60% of nationwide animal protein consumption.

Moreover, fish contributes to 3.50% of gross domestic product (GDP), 25.72% of agricultural GDP, and 1.23% of export earnings. In 2018–2019, Bangladesh exported 33,362 tons of saltwater shrimp and freshwater prawn worth at USD 383 million [2].

Despite widespread benefits, aquaculture in Bangladesh has recently encountered concerns due to climate change, as several climatic threats to fish production have been recognized [3,4]. The potential effects of climate change on fish production could have serious concerns for the economy of Bangladesh. While coastal fish production is more susceptible than inland aquaculture [3], imminent climate change will critically affect overall aquaculture production. Considering exposure to the effects of environmental change on fish production, appropriate adaptation strategies should be identified to manage the challenges. Minimizing the impacts of environmental change on aquaculture will need both adaptation policies and strategies [5]. Identifying possible adaptation mechanisms and mitigation options would help to intensify resilience to climate change in aquaculture [6].

Considering vulnerability to the effects of climate change on aquaculture, one of the potential adaptation options is tilapia culture [6,7]. In Bangladesh, tilapia aquaculture has great potential, as tilapia can be produced in freshwater, brackish water, and saltwater conditions. The aim of this paper is to identify how tilapia aquaculture can adapt to climate change in Bangladesh. Moreover, it examines about tilapia culture systems, productivity, and physiological responses to climate change. Finally, we conclude with some options for how tilapia culture can be adapted to climate change.

2. Climate Change in Bangladesh

Geographically, Bangladesh is one of the world's vulnerable countries to climate change because of its location and climatic condition. According to the Global Climate Risk Index, Bangladesh is positioned 7th among countries susceptible to climate change [8]. Bangladesh is vulnerable to different climatic factors, including rainfall variation, flood, drought, temperature fluctuation, and salinity change [3,4].

Global warming has changed wind forms, directing to enhanced rainfall in Bangladesh. In fact, global warming alters rainfall patterns as the water holding ability of air raises 6–7% for each 1 °C increase in temperature [9]. Bangladesh is located in the massive rainfall region due to its proximity of the Himalayas in the north and the monsoon belt with the Bay of Bengal in the south. In Bangladesh, annual precipitation varied from 1400 to 4300 mm, and the mean annual rainwater intensified at a rate of 5.52 mm during 1958–2007 [10]. Climate change has great effects on rainfall irregularity, and monsoon precipitation is projected to strengthen about 10–15% by 2030 [11].

Bangladesh is a flood-prone country which has encountered six severe floods with over 35% of inundation since 1980 [12]. Massive rainfall is one of the reasons for intensified flooding in Bangladesh. The mean temperature in Bangladesh is predicted to increase by 1.4 °C by 2050 and 2.4 °C by 2100 [13], and a 2 °C intensify in temperature could cause a 29% increase in flood area [14]. Moreover, river flooding is common in Bangladesh as the country has 700 rivers (Bangladesh is often called the “land of rivers” because of the extensive network of rivers crisscross the country) including 57 transboundary rivers. In Bangladesh, 14.6 million coastal people are susceptible to flood, which will increase to 18.5 million by 2050 [15].

The typical weather in the dry season of Bangladesh is drought. Bangladesh encountered 19 droughts during the last 50 years [16]. In Bangladesh, drought can be categorized into meteorological, hydrological, and seasonal drought [17]. Seasonal drought, which is common in Bangladesh, has recently intensified due to climate change. Seasonal drought is connected to inadequate precipitation due to global warming [9]. In the tropical Pacific Ocean, global warming relating to El Niño (El Niño refers to the cycle of hot temperatures that happens across the tropical Pacific Ocean) can alter rainfall into dry mode, causing drought [18,19].

Coastal Bangladesh is prone to cyclones that originate in the Bay of Bengal as well as the Indian Ocean. Bangladesh was affected by 154 cyclones, including 43 severe cyclones,

during 1877–1995 [20]. On average, an extreme cyclone affects Bangladesh every three years [12]. The intensity of cyclones has increased by 5–10% in Bangladesh [21]. Coastal Bangladesh was affected by tropical cyclone Sidr in November 2007 with financial damages of USD 1.67 billion [22]. In recent years, cyclones Nargis, Rashmi, Aila, Bijli, Giri, Mahasen, Komen, Roanu, Mora, Bulbul, and Amphan devastated coastal Bangladesh.

The coastline of Bangladesh is 710 km long [23]: it is a crucial zone for sea level rise because of global warming and glacier melting [24]. Bangladesh lies just 2 m above sea level [25]. The annual sea level rise in Bangladesh is 15.9–17.2 mm [26], whereas the global annual sea level rise is 2–3 mm [25]. A 45 cm sea level rise would cause 11% flooding in Bangladesh that will generate millions of people as “climate refugees” [14]. The sea level is expected to rise by 1 m by 2100 [27], which would affect the Sundarbans mangrove forest (the Sundarbans, which is a transboundary mangrove forest located along the mouth of the Bay of Bengal between Bangladesh and India, is the world’s largest continuous mangrove forest). The sea level rise is projected to inundate 120,000 km² of coastal Bangladesh [21].

Saltwater intrusion from the Bay of Bengal, can enter over 100 km towards inland [22,28], is a common problem in coastal Bangladesh. Cyclones, sea level rise, and tidal surges play critical roles in enhancing salinity [20]. Salinity in coastal rivers has recently increased to 13 ppt in the dry season and 4 ppt in the monsoon [29]. In Bangladesh, 1.05 million ha of coastal land has been affected by saltwater [21], an areas which is increased to 2 million ha by 2050 [19].

In the Bay of Bengal, the sea surface temperatures are growing more rapidly than in the oceans globally. The global sea surface temperature is 1 °C higher than 140 years ago [30]. During 1985–2009, the water surface temperature in the Bay of Bengal increased from 0.20 to 0.46 °C during the day and 0.30 to 0.48 °C at night, which is expected to increase from 0.35 to 0.72 °C during the day and 0.50 to 0.80 °C at night by 2050 [31]. Even small increases in water temperature cause sub-lethal effects for tropical fish [32].

3. Tilapia Aquaculture in Bangladesh

3.1. History of Tilapia Farming

As a first exotic piscine, the Mozambique tilapia (*Oreochromis mossambicus*) was introduced to Bangladesh from Thailand in 1954 [33]. However, the acceptance level of this species was not satisfactory to the farmers because of its early maturation and frequent spawning behavior that leading to overcrowding and slow growth rates [34]. After two decades, in 1974, UNICEF (United Nations International Children’s Emergency Fund) introduced the Chitralada strain of Nile tilapia (*O. niloticus*) to overcome these constrains [35], because of its hardy nature, faster growth, and high disease resistance [36]. Nonetheless, Nile tilapia also struggled as a culture species due to a lack of knowledge about management practices and biology, and thus, cannot attract farmers who have a strong affinity to carp culture, which is very popular in Bangladesh. A continued attempt was made to make tilapia popular through importing red tilapia (*O. mossambicus* × *O. niloticus*) from Thailand. Afterwards, the Bangladesh Fisheries Research Institute (BFRI) reintroduced Nile tilapia in 1987 and red tilapia in 1988 from Thailand [34]. The WorldFish Center, previously known as the International Center for Living Aquatic Resources Management (ICLARM) developed a synthetic strain of *O. niloticus* that is popularly known as Genetically Improved Farmed Tilapia (GIFT), which was further improved by the BFRI and introduced to Bangladesh in 1994 [37,38]. Moreover, the GIFT strain showed significantly better performance compared to other tilapia in numerous aspects [39,40]. Subsequent research was carried out to produce all male sex-reversed GIFT to avoid prolific breeding, commonly known as monosex tilapia [41].

After gradational introduction, tilapia has been becoming popular among fish farmers in Bangladesh. Tilapia aquaculture plays a vital role in fish production, distribution, marketing, and consumption, which contributes to the value adding process, and greater role in increasing food supply [42]. Tilapia is now the third most important fish species after pangas and rohu in Bangladesh (Figure 1). Due to its significant contribution to food

production, tilapia is commonly known as “aquatic chicken” [43]. In fact, tilapia can play a major role as a source of low-priced animal protein in the same way as chicken. Tilapia has also been called as the “everyman’s fish” [44].

Figure 1. Species wise annual inland fish production in 2018–2019 [2].

3.2. Tilapia Culture in Freshwater Systems

Tilapia is well recognized as a suitable species for freshwater aquaculture systems in Bangladesh. The culture duration of tilapia is usually few months from April/May to November/December to allow more than one culture cycle [45]. Tilapia culture is mainly season based, starting prior to the summer and lasting until winter. As tilapia farming is completely dependent on hatchery-produced fry, culture season, stocking density, and culture duration are important factors. Tilapia can be cultured in small-scale, large-scale, low-input, or high-input operations in inland waterbodies. Tilapia culture can be classified into polyculture, monoculture, and integrated farming. Based on the level of input, tilapia culture can also be categorized as extensive, semi-intensive, and intensive.

Tilapia pond polyculture with other species (mostly carp) has been traditionally practiced in rural Bangladesh. Polyculture is usually practiced with a low or medium level of input under extensive or semi-intensive culture systems. Polyculture is based on the proper utilization of different ecological niches of a pond to obtain maximum yield per unit area [46]. Tilapia feed on organic particles available on the pond bottom, which are re-suspended by the sediment tabulation of carp species in the polyculture system. In this manner, tilapia can prevent the lifting of the organic load in the sediment, which in turn provides anaerobic conditions [47]. The stocking density of tilapia in polyculture system may vary depending on the culture species, natural food availability, and supplementary diet. For example, the inclusion of Nile tilapia at 2000/ha in a polyculture of bottom dweller common carp (*Cyprinus carpio*) and phytoplankton filter-feeding rohu (*Labeo rohita*), stocked at 5000 and 15,000/ha, increased the nutrient concentrations in ponds, reduced phytoplankton biomass and suspended solids, which resulted in additional fish production without affecting other cultured species [48]. Nile tilapia with a stocking density of 2200/ha in a polyculture system including filter-feeders 1000/ha of catla (*Catla catla*), 3000/ha of rohu (*L. rohita*), and 3000/ha of silver carp (*Hypophthalmichthys molitrix*) with 4000/ha of freshwater prawn (*Macrobrachium rosenbergii*) and 10,000/ha of mola (*Amblypharyngodon mola*) increased the production and economic benefits [49]. The stocking density of tilapia at 10,000/ha in polyculture with prawn was also found to be suitable for the growth of both tilapia and prawn [50,51]. In a periphyton-based polyculture system, a stocking ratio of 75% GIFT with 25% prawn at a total stocking of 20,000/ha resulted in suitable fish production

and economic returns [52]. Tilapia with prawn in polyculture system supplemented with 30% of protein also showed better performance [53].

On the contrary, monoculture allows single species tilapia production with high stocking density with high level of feed inputs, and thus, higher yield than polyculture. Although tilapia is a suitable species for polyculture due to its uninterrupted parallel production with other species, in recent times in Bangladesh have preferred to farm tilapia in monoculture. Higher growth with high stocking density under intensive or semi-intensive farming is the main key point for tilapia monoculture. A stocking density (80–200/decimal or 20,000–50,000/ha) of tilapia in monoculture can be 10–20 times higher than polyculture [54–56]. Monoculture production is also dependent on the feeding frequencies, as four times feeding frequency shows a better growth of monosex male tilapia [57].

Based on biological criteria, tilapia has potential for cage culture. Tilapia is usually produced in cages under polyculture or monoculture. Tilapia cage culture in Bangladesh is considered a very popular and effective production system in open water. Tilapia cage culture can be a successful alternative way to eliminate poverty in poor rural communities in Bangladesh [58]. Growth performance and economic analysis show that the stocking density of 50 monosex tilapia per m³ is the best for cage culture in Kaptai Lake in Bangladesh [58]. Moreover, tilapia production in cages could increase more than pond yield if they are fed with floating commercial diets supplemented with zymetin probiotics [59]. Tilapia culture is profitable if cages are designed in an inexpensive way with adaptive management techniques [60].

Tilapia culture under rice–fish farming is a potential system of fish production that would not hamper rice yield in Bangladesh. Rice–fish integration has potential to utilize land and water for the fulfillment of protein demand and increase the incomes of farmers [61]. In rice–fish coculture, tilapia is a promising species due to its higher adaptability and better growth compared to other species [62]. The stocking density of tilapia in rice–fish coculture can be varied due to extensive farming. Farm size can affect the stocking density, where a medium sized farm with 5000/ha monosex tilapia in a rainfed rice–fish ecosystem can offer better economic benefit [63]. Besides, 6 per m² tilapia combined with common carp in integrated rice–fish system is a suitable stocking density for better growth, survival, and maximum rice production [64]. The inclusion of tilapia with 2500/ha in freshwater prawn–mola polyculture in rotational rice–fish farming showed better production and profit [65]. Rice–tilapia coculture can also be more viable with the incorporation of basal fertilization in combination with compost fertilizer [66]. Integrated rice–tilapia culture, particularly seed production, could be one of the best approaches to reduce the tendency of farmers to use pesticides along with the increase in rice–fish production [67,68].

In Bangladesh, tilapia is also produced in pen culture. A pen is a fixed enclosure in which the bottom is the bed of the water body. In pen aquaculture, a 1.5–2.5 m depth of water in canals, oxbow lakes, and dead rivers with a high eutrophic status is considered as ideal and a soft muddy to hard sandy bottom is preferable for fish growth [69]. Tilapia pen culture under floodplain aquaculture is becoming popular in rural Bangladesh.

3.3. Coastal Brackish Water Tilapia Culture

Shrimp (*Penaeus monodon*) is considered a major species for brackish water aquaculture in coastal Bangladesh, which is one of the largest sectors for earning foreign currency [70]. Recently, shrimp production has been struggling due to environmental degradation with climate change and disease outbreaks [71]. To overcome this situation, farmers have been looking for an alternative method where crop diversification, such as polyculture instead of shrimp monoculture, can play an effective role in sustainable aquaculture. Tilapia can play a vital role in polyculture to compensate for partial economic loss due to unexpected mortality of shrimp [72]. Although tilapia is a very popular freshwater aquaculture species in Bangladesh, it can grow as a diversified crop in brackish water systems [37,73]. Tilapia can augment the production of shrimp because of cumulative environmentally friendly polyculture conditions as they utilize different ecological niches [74]. In fact, tilapia feed on

the upper water layer, filtering phytoplankton and zooplankton [47], while shrimp mostly stay on the pond bottom for grazing substrate and detritus [75]. Moreover, tilapia can tolerate various environmental hazards [76], particularly salinity stress ranging from 0 to 25 ppt [73,77].

Three types of tilapia–shrimp polyculture systems are generally constructed, including simultaneous, sequential, and crop rotation systems [78]. Among different strains, GIFT and Nile tilapia would be most suitable candidate for brackish water aquaculture due to their 36–81% higher growth performance [79] and wide range of salinity tolerance compared to available salt tolerant species (grey mullet, silver barb, pangus) for shrimp polyculture. Shofiquzzoha and Alam [74] found that GIFT and shrimp coculture with 10,000/ha stocking density is more prosperous than the culture of silver barb and shrimp with the same density under polyculture. Studies also recommended that a stocking density for shrimp of not more than 2/m² [80,81], and for GIFT 1/m² [80] is feasible under extensive culture. In addition, monosex tilapia (10,000/ha) with prawn (20,000/ha) culture showed better performance even though water salinity varied greatly, from 3 to 10.3 ppt [82].

3.4. Productivity

Tilapia production was not initially satisfactory in Bangladesh. However, with the advancement of culture systems, converting extensive to semi-intensive or intensive culture following monoculture instead of polyculture, the productivity of tilapia has increased considerably. Total tilapia production in inland waterbodies has recently increased from 370,017 tons in 2016–2017 to 390,559 tons in 2018–2019 (Table 1). Tilapia productivity has gradually increased in most culture systems. However, tilapia production can vary depending on culture system and species. The highest average tilapia productivity was found in pond systems under freshwater aquaculture, followed by seasonal water body and cage–pen culture. Tilapia grows to a marketable size (100–150 g) within a short culture period (2–3 months), which facilitates farmers to produce more than one crop in a year [59]. The highest annual production of monosex tilapia under monoculture is around 10,000 kg/ha [83], and the production of tilapia is 8028 kg/ha with carp [84].

Table 1. Recent tilapia production under different culture systems in Bangladesh.

Culture System		Tilapia Production (Metric Ton)		
		2016–2017	2017–2018	2018–2019
Freshwater aquaculture	Pond system	306,556	316,283	320,963
	Seasonal waterbody	21,904	21,986	22,086
	Cage and pen culture	5744	6203	6811
Brackish water aquaculture	Prawn and shrimp farm	33,882	38,465	38,789
Total		370,017	384,737	390,559

Source: Extension Data (2020).

4. Tilapia Aquaculture: Adaptation to Climate Change

4.1. Low Water Quality

The positive culture characteristics of tilapia are their tolerance to poor water quality. Tilapia usually have lower oxygen requirements than other fish, such as carp. In turbid water, tilapia can easily survive up to 200 mg/L levels of turbidity with no significant effects on specific growth rate (SGR) and feed conversion ratio (FCR) [85].

Tilapia can also tolerate certain levels of water pollution. Flooding is common in Bangladesh during the monsoon leading to intense rainfall which can inundate canals and rivers in low-lying areas. Industrial and agricultural wastes are discharged into canals and rivers. Polluted waters are mixed with floodwaters during the monsoon and spread over unavoidable flood areas. Therefore, culturing pollution tolerant species can reduce

the risk of production loss. In this sense, tilapia can play a substantial role in tackling these conditions. Nile tilapia (*O. niloticus*) can tolerate high levels of waterborne cadmium, which is a common toxicant of polluted water. The highest level of cadmium recorded for Nile tilapia was 96 h LC50 (14.8 mg/L Cd; hardness 50 mg/L CaCO₃) and branchial chloride cell numbers started to recover after 24 h of exposure [86].

Tilapia can survive under dissolved oxygen conditions as low as below 2.3 mg/L if other factors such as temperature and pH remain favorable. In the rainy season, dissolved oxygen levels may reduce due to the increase in turbidity, and oxygen levels may reach as low as 2 mg/L. Low dissolved oxygen levels ranging from 1–1.5 mg/L have no effect on tilapia survival [87]. In addition, algal bloom in a fertilized pond can also reduce oxygen levels to 0.3 mg/L, but no tilapia mortality was reported [88].

4.2. Drought Condition

As a consequence of climate change, farmers often suffer from low water volume in drought conditions because of rainfall variation in different regions of Bangladesh. Seasonal and metrological drought conditions cause inadequate access to water on fish farms. Severe droughts often cause short culture periods for fish. Prolonged droughts with low groundwater levels are also a concern for water shortage on fish farms. Year-round fish production is not feasible as a result of low water levels as well as water scarcity in ponds. Most fish farms including ponds dry up during the dry season, causing unfavorable conditions for fish, and thus fish become more stressed and crowded in low levels of water.

In the summer season, the water depth in fishponds can reduce up to 100 cm and sometimes lower than that. Surprisingly, tilapia can easily survive in water depths as shallow as 50 cm, though suitable growth was recorded at around 100 cm water depth [89], whereas carp need a minimum of 180 cm water volume in the pond for their suitable growth [90]. Thus, it can be presumed that tilapia can adapt to lower water volumes than other species due to drought condition and rainfall variation.

Pumping groundwater to irrigate ponds can help tilapia culture in the dry season. Rainwater harvesting with storage facilities in ponds and ditches may also help with tilapia culture in the dry season. Using rainwater for tilapia culture may increase water use efficiency. Adjusting tilapia culture in floodplain seasonal waterbodies during monsoon may also help to cope with drought.

4.3. Temperature Fluctuation

Temperature change—either seasonal or daily—is a common phenomenon in aquatic environments. Fish, which are critically important inhabitants of aquatic environments, cannot avoid temperature changes. Hence, adaptations, acclimatization, and physiological responses against temperature changes are the only survival techniques of fish. It is generally perceived for living organisms that “more adaptive capability—more distribution”. The worldwide distribution of tilapia confirms this perception and different studies also support this notion. Table 2 summarizes the effects of temperature changes on the physiological alterations of tilapia. The thermal effects on tilapia showed that growth performance significantly decreased after at 34 °C, although this showed a decreasing tendency towards high temperature changes [91–96]. Before they reached 5 days old tilapia (*O. mossambicus*) showed significantly increased percentages of deformity, and a greater number of males was induced by high temperature (28 and 32 °C) after 10 days [97]. According to Desprez and Mlard [98], a higher proportion (98%) of male blue tilapia (*Oreochromis aureus*) are produced during sex determinism in high temperature regimes (34 °C). Non-specific immunity (lysozyme activity) of Nile tilapia can significantly decrease due to high temperature (33 °C) [99]. Recently, Islam et al. [96] found variable effects of high temperature (37 °C) on the hemato-biochemical parameters of tilapia. Here, the abundance of hemoglobin and red blood cells were significantly reduced, although the amount of white blood cells and blood glucose were increased. Higher temperature (31 °C) also showed positive effects on

the metabolism of tilapia and greater growth was observed, which was supported by the increased digestive enzymes genetic expression [100].

On the other hand, at low temperatures, tilapia survivability suffers. Significantly decreased growth performance and mortality rate were perceived for tilapia below 21 °C [89,101]. It was also observed that low temperature significantly decreases hematocrit and hemoglobin parameters [101]. In addition, at temperatures below 11 °C, tilapia stop feeding, with high stress, fungal infection, and mortality due to decreases in plasma osmolarity, chloride, and sodium ion concentrations [89,102]. The exposure of tilapia larvae to low temperature (20 °C) of tilapia larvae before they were 10 days old induced a high ratio of females during sex differentiation [97]. A low temperature (13 °C) decreased serum glucose and cholesterol levels but increased cortisol levels of GIFT. Moreover, low temperatures also enhance catalase, glutathione, and superoxide dismutase levels in the liver with oxidative damage [103]. It was also found that reduced temperature decreases saturated fatty acid content, though it increases the polyunsaturated fatty acid content [104]. Gene expression analysis suggests that when tilapia are exposed to low-temperatures (10 °C), significant changes were viewed in the expression of genes associated nucleic acid and protein synthesis, amino acid metabolism, lipid and carbohydrate content, and immunity [105]. Acute lethal low temperature (8 °C) can disrupt kidney function and downregulate the immune-related pathway in the kidney of tilapia [106].

Tilapia is a thermophilic species. The ultimate upper lethal temperature for *T. mossambica* lies at 38 °C [107]. Recent studies showed that tilapia can tolerate temperatures of up to 34 °C without any significant effect on their growth rate [94,96]. In addition, the cortisol level, which is the stress indicator in tilapia, does not significantly increase even at 36 °C [108], which suggests that tilapia can tolerate high temperatures, whereas for *L. rohita*, another commonly cultured species in Bangladesh, a temperature of 36 °C may be hazardous for growth and can cause physiological damage [109–111]. The balanced sex ratio of *O. niloticus* does not deviate significantly even up to 36 °C [92]. A study on the haemato-biochemical parameters also revealed that temperatures up to 34 °C may not be hazardous for Nile tilapia [96]. A comparative study suggests that embryonic development and hatching of carp are significantly affected even at 33 °C [112]. However, Nile tilapia showed faster embryonic development and better survival rates (52.7%) after hatching at 34 °C than the control group (49.5%) at temperature 27 °C [113]. Tilapia may adopt some behavioral or physiological mechanisms for this high temperature tolerance. In fact, tilapia may adjust to extreme temperatures with their diurnal movement in open water. Tilapia can show other behaviors such as ventilation cessation behavior and aquatic surface respiration to prolong thermal tolerance limits both in freshwater and saltwater in response to thermal changes [114].

Different strains of Nile tilapia differ with respect to cold tolerance, but growth is usually hampered at temperatures under 16 °C. Although most fish species start to stop feeding at low temperatures (below 16 °C) in winter season [115], most strains of tilapia become severely stressed at 13 °C. Nile tilapia started to die when water temperature fell to 11 °C, and 100% death occurred by 7.4 °C. Low temperature ranges from 11 to 8.4 °C are lethal for the GIFT strain [116]. Cold acclimation can reduce triglyceride and total cholesterol in GIFT, which can help enhance cold tolerance [104]. Since the average low-temperature of Bangladesh in winter is 12.7 °C, tilapia can easily survive in winter even at low temperatures, and this low temperature tolerance can be improved through the use of 0.2% *Astragalus membranaceus* extract powder [117].

Table 2. Physiological responses of tilapia for the effects of temperature.

Tilapia Strain	Temperature	Stage	Exposure Time (Day)	Effect	Reference
Tilapia (<i>O. mossambicus</i>)	20–32 °C	Larvae	0–10	<ul style="list-style-type: none"> Deformity significantly increase when tilapia kept in high temperatures (28 and 32 °C) before 5 days of age Exposure to lower (20 °C) temperature before 10 days old induced a high proportion of females 	[97]
Nile tilapia (<i>O. niloticus</i>)	25–37 °C	Juvenile	21	<ul style="list-style-type: none"> SGR in wet weight and fecal energy significantly lower in high temperature (37 °C) while there is no significant difference at 25–34 °C Protein retention efficiency highest at 28 °C and lowest at 37 °C 	[94]
Nile tilapia (<i>O. niloticus</i>)	31–37 °C	Fingering	60	<ul style="list-style-type: none"> Growth performance (weight gain, SGR) decrease at 34 °C but significantly decline at 37 °C compared to 31 °C 	[96]
Nile tilapia (<i>O. niloticus</i>)	15–30 °C	Fingering	60	<ul style="list-style-type: none"> Growth performance significantly decreases at 15 and 20 °C Survival and growth rate high at 25 and 30 °C 	[101]
Red, GIFT and Supreme Nile tilapia strains	22–30 °C	Fry	120	<ul style="list-style-type: none"> Red, GIFT, and Supreme strain present similar growth and fit of exponential model at 22 °C GIFT and Supreme strain present higher growth rate at 30 °C compared to Red strain 	[118]
Nile tilapia (<i>O. niloticus</i>)	25–31 °C	Larvae	13	<ul style="list-style-type: none"> High growth when larvae reared at thermocycle (31 °C: 25 °C) than at 28 °C Most analyzed genes of digestive enzymes display daily rhythms in the thermocycle group 	[100]
Egyptian tilapias strains	16–33 °C	Fry	133	<ul style="list-style-type: none"> Weight increase with the increase in temperature 	[119]
Nile tilapia (<i>O. niloticus</i>)	20–34 °C	Juvenile	56	<ul style="list-style-type: none"> Optimal temperature/dietary protein level combination (30 °C/40%) shows the greatest SGR (2.748%) per day 	[95]
Nile Tilapia (<i>O. niloticus</i>)	27–37 °C	Juvenile and fry	45–60	<ul style="list-style-type: none"> Mean survival, weight, length, daily growth rate, and FCR significantly reduce at 35 and 37 °C compared to 27 and 32 °C 	[93]

Table 2. Cont.

Tilapia Strain	Temperature	Stage	Exposure Time (Day)	Effect	Reference
Sex reversed Nile tilapia (<i>O. niloticus</i>)	25–35 °C	Fry	30	<ul style="list-style-type: none"> Highest male ratio and mortality rate (91.50% and 17.13%) obtained at 35 °C Highest significant weight gain at 30 °C 	[120]
Nile tilapia (<i>O. niloticus</i>)	5–33 °C	Fingerling	300	<ul style="list-style-type: none"> Fish growth significantly increases above 21 °C and reduces significantly below 21 °C Fish stop feeding below 10 °C with stress, fungal infection, and high mortality 	[89]
Sex reversed Nile tilapia (<i>O. niloticus</i>)	26–32 °C	Fry	28	<ul style="list-style-type: none"> Temperatures 26–32 °C do not affect sex reversal rate, but temperatures around 30 °C improve growth and survival 	[121]
Nile tilapia (<i>O. niloticus</i>)	18–33 °C	Fingerling	28	<ul style="list-style-type: none"> Plasma lysozyme activity increases at 28 °C after 2–4 weeks A significant decrease in lysozyme activity at 33 °C for 4 weeks 	[99]
Nile tilapia (<i>O. niloticus</i>)	20–28 °C	Fingerling	30	<ul style="list-style-type: none"> Growth and survival rate do not significantly decrease at 20 and 24 °C FCR increase with temperature, but difference between 28 and 30 °C is not significant 	[122]
Nile tilapia (<i>O. niloticus</i>)	20–39 °C	Juvenile	28	<ul style="list-style-type: none"> At 37 °C survival and growth average 41.9% and 74.5% of those fish reared at 27–33 °C, resulting in a production loss over 70% 	[91]
Nile tilapia (<i>O. niloticus</i>)	22–37 °C	Juvenile	28	<ul style="list-style-type: none"> Average weight significantly higher at 26 and 30 °C than at 22 and 34 °C Daily weight gain and FCR are better at 26 and 30 °C At 37 °C higher ratio of males (64–80%) is produced with 60–81% survival 	[92]

Bangladesh is called a country of six seasons, though three seasons (summer, autumn and winter) are mainly observed. Water temperature fluctuates throughout the country year round [123]. A survey report showed that monthwise average water temperature varied in the last five years by even more than 1 °C in some months (Table 3).

Table 3. Average water temperature in Bangladesh (data were collected from Dhaka, Chittogong and Cox's bazar areas and adopted from sea water temperature info [123]).

Year	2017	2018	2019	2020	2021	Temp. Fluctuation (2017–2021)
Month	Temperature (°C)					
January	21.87	21.20	21.37	20.63	22.27	0.40
February	22.07	21.87	21.9	21.2	22.3	0.23
March	25.57	26.00	25.17	24.93	26.63	1.07
April	25.57	26.00	25.17	24.93	26.63	1.07
May	27.73	27.97	28.03	28.13	29.03	1.30
June	28.53	28.73	28.80	29.33	28.87	0.33
July	28.23	27.90	28.30	28.97	28.80	0.57
August	28.53	28.57	28.47	28.73	28.73	0.20
September	28.83	28.93	28.73	29.03	29.10	0.27
October	28.37	28.33	28.20	28.47	29.23	0.87
November	25.87	26.00	25.57	26.60	26.57	0.70
December	23.57	23.43	23.00	22.83	23.20	−0.37

4.4. Salinity Change

Tilapia is considered as euryhaline fish which can grow comfortably both in freshwater and brackish water [124,125]. However, changes in water salinities can decrease growth performance and can alter the physiology of tilapia. For example, Nile tilapia can grow better when reared in water with a salinity of up to 7 ppt (salinity is usually measured in parts per thousand (ppt), which is equivalent to grams of salt per liter water (g/L)) [126,127], while *T. rendalli* can tolerate 10 ppt salinity with no significant effect on their growth [128]. The salinity tolerance of another strain Rufiji tilapia (*Oreochromis urolepis urolepis*) is higher than other tilapia strains; it is 25 ppt in which concentration SGR, daily growth rate, and total body weight showed higher rates even than in 5 ppt salinity [129]. In fact, the salinity tolerance of tilapia may be strain specific. Since Nile tilapia is a widely cultured species, most research has performed to evaluate the salinity tolerance of this species, the findings of which are summarized in Table 4.

Although, Nile tilapia grows well in low salinity (4–7 ppt), slightly higher salinity (8 ppt) significantly decreases average weight gain [130,131]. Other studies indicate conflicting results of salinity in the same concentration, where the highest survival (98%) and a linear growth in net biomass of Nile tilapia were observed at 8 ppt water salinity in recirculating systems [132], and this salinity is also recommended in biofloc technology [133]. These results suggest that rearing techniques may have the least effects on the salinity tolerance of Nile tilapia. Interestingly, the best survival and growth rate of Nile tilapia was obtained at a salinity of 16 ppt [134]. Similarly, the nutrient digestibility of Nile tilapia was increased at a salinity of 15 ppt and showed a large impact on the distal region of the intestine [135]. Moreover, Nile tilapia cultured at 16 ppt observed greater results than those cultured at 20 ppt due to lower death rates and higher expression of ion-regulated genes [136].

Besides growth parameters, salinity concentration also influences hematological parameters of Nile tilapia. According to de Azevedo et al. [127], hematocrit and the erythrocyte count significantly decrease at high water salinity (14 ppt). The authors also observed histological and histopathological alterations with the increased intensity of salinity. Polyunsaturated fatty acids significantly increased up to 16 ppt salinity [131]. The levels of Na^+ , Cl^- and Ca^{2+} and white blood cells increased significantly in Nile tilapia when exposed to 10 and 15 ppt salinity [137].

Ideally, tilapia is a potential candidate to cope with salinity changes. Endocrine studies revealed that tilapia can compensate for greater changes in external osmolality while cultured in a tidal salinity, maintaining osmoregulatory parameters similar to seawater-acclimated fish [138,139]. Salt tolerance genes in Nile tilapia, which play vital role during adaptation in saltwater, were also identified [140]. For saltwater adaptation, Watanabe

et al. [141] suggested that the progeny of red tilapia spawned and cultured through early ontogenetic development in brackish water are well adapted for growth in brackish and seawater, and may have greater resistance to cold stress in seawater than progeny spawned in freshwater.

Table 4. Physiological responses of tilapia for the effects of salinity.

Tilapia Strain	Salinity	Stage	Exposure Time (Day)	Effect	Reference
Florida Red Tilapia	4–36 ppt	Juvenile	70	Significantly better growth for progeny spawned at 18 ppt than 4 ppt	[141]
Nile tilapia (<i>O. niloticus</i>)	0–16 ppt	Fingerling	70	Salinity 4–8 ppt suitable for biofloc technology to improve growth performance in initial culture phase	[133]
Nile tilapia (<i>O. niloticus</i>)	0–21 ppt	Fry	45	Culture possible up to 7 ppt salinity without hampering growth and haematological parameters	[127]
Nile tilapia (<i>O. niloticus</i>)	8–25 ppt	Adult	88	Highest survival (98%) and linear growth in net biomass at 8 ppt	[132]
Nile tilapia (<i>O. niloticus</i>)	0–15 ppt	Fry	96	The tested strains at 5 ppt and returned from 15 ppt to freshwater revealed higher growth rate than the same strains in salinity and freshwater	[142]
Nile tilapia (<i>O. niloticus</i>)	8–24 ppt	Juvenile	15	No difference in antioxidant index at 8 ppt relative to the control; polyunsaturated fatty acid increase up to 16 ppt	[131]
Tilapia (<i>Tilapia rendalli</i>)	5–15 ppt	Juvenile	70	Apparent digestibility of ash, crude protein, fat, and gross energy significantly higher at 10 ppt salinity	[128]
Nile tilapia (<i>O. niloticus</i>)	0–10 ppt	Fingerling	28	All fish survive at 0–7 ppt, most preferred salinity 1 ppt	[126]
Tilapia (<i>O. mossambicus</i>)	0–35 ppt	Fry	60	Culturing fish under tidally changing salinities elicits a different pattern of endocrine regulation	[143]
Tilapia (<i>O. mossambicus</i>)	0–35 ppt	Yolk-sac larvae	120	Tilapia culture in a tidally changing salinity has adaptive advantages compared with fish produced in freshwater when facing a hyperosmotic challenge	[139]
Tilapia (<i>O. mossambicus</i>)	0–35 ppt	Yolk-sac fry	120	Tilapia in a tidally changing salinity can compensate for large changes in external osmolality while maintaining osmoregulatory factors within a limited range close to seawater acclimated fish	[138]
East Java strain (<i>O. niloticus</i>)	0–15 ppt	Fingerling	14	The concentrations of serum Cl^- , K^+ , Na^+ , and Ca^{2+} in fish acclimated at 0 and 5 ppt are not significantly different; white blood cells do not increase significantly below 10 ppt	[137]
Nile tilapia (<i>O. niloticus</i>)	0–15 ppt	Fingerling	60	Salinity 15 ppt increases nutrient digestibility, but enhanced digestibility diminished over time	[135]

Table 4. Cont.

Tilapia Strain	Salinity	Stage	Exposure Time (Day)	Effect	Reference
Rufiji Tilapia (<i>O. urolepis urolepis</i>)	5–35 ppt	Fry	56	Fry reared at 25 ppt salinity has highest final body weight, SGR, weight gain, and daily growth rate, while lowest at 5 ppt	[129]
Nile tilapia (<i>O. niloticus</i>)	0–34 ppt	Fry	22	The minimum and maximum osmotic work rate, best survival, and growth rate are obtained at 16 and 34 ppt salinity, respectively	[134]
Nile tilapia (<i>O. niloticus</i>)	6–20 ppt	Young	180	Fish reared at 16 ppt has better performance than that of 20 ppt due to lower mortality and higher expression of ion-regulated gene	[136]

4.5. Disease and Parasite Prevention

Climate change may affect water quality and disrupt host–pathogen interactions [144], sometimes creating beneficial conditions for pathogen amplification and spread [144–146], or for microbial and ecological dysbiosis [147]. Water quality disruptions stemming from climate change that may have consequences for the outbreak of marine parasites and diseases include changes in temperature, hypoxia, CO₂ accumulation (reduced pH), precipitation (leading to increased or decreased salinity), and cyclone frequencies and intensities [144,148]. Changes in water quality may result in immediate impacts on host–pathogen equilibriums or long-term impacts such as the expansion of hosts (primary and secondary) and pathogens into new regions [149]. Hence, these challenges for aquaculture need to be considered to be caused by climate change [150]. In fact, environmental change with pathogens and parasites outbreaks may be accelerated due to climate change.

Disease-resistant fish species can play critical role in mitigating these challenges, and tilapia is a suitable candidature in this context. It has been reported that tilapia are resistant to most diseases and parasites [151], and hybrid tilapia (male blue tilapia x female Nile tilapia) has higher disease resistance than blue tilapia and Nile tilapia [152]. Disease-resistant tilapia can be developed following selective breeding program against viral [153] and bacterial diseases, as host resistance is highly heritable in a Nile tilapia breeding populations with GIFT origin [154]. In addition, selective breeding can be performed with high accuracy using Bayesian models followed by marker-based and pedigree-based genomic prediction against Streptococcosis diseases [155].

Disease avoidance or removal is not an easy task if soil and water of aquatic environment are infected with pathogens. Therefore, prevention is the best choice for maintaining sustainable aquaculture. However, collecting disease-free stock, avoiding overfeeding, minimizing unnecessary handling, reducing overcrowding, and removing dead fish will reduce the risks of disease outbreak [156,157]. Moreover, regular cleaning and disinfection of equipment and production units must be performed to reduce the transmission of pathogens. Maintaining water quality in farming systems is also essential [157]. In addition, different feed supplements such as probiotics [158], *Aloe vera* [159], assam tea extract [160], *Sophora flavescens* [161], corncob [162], vitamin C [163], orange peels [164], green tea [165], ginger [166], and Indian lotus leaf powder [167] can increase the disease resistance of tilapia. On the other hand, novel effective vaccines can also play an important role in disease prevention and control: vaccines have been developed against most common pathogens of tilapia—Streptococcosis [168,169], motile aeromonad septicemia [170], tilapia lake virus [171], and infectious hematopoietic necrosis virus [172]. Using a treatment and diagnosis system to alert farmers to the occurrence of bacterial infection in tilapia can be a very useful tool that can reduce economic losses and labor costs in aquaculture [173].

5. Conclusions

Aquaculture in Bangladesh is susceptible to a variety of climatic factors, including global warming, rainfall variation, salinity change, and temperature fluctuation. Considering susceptibility to the impacts of environmental change on aquaculture, tilapia farming is one of the potential strategies for adaptation to climate change. Compared to other fish, tilapia can adapt to low water quality caused by rainfall variation as well as flood and drought. Tilapia can also adapt to low water volume and drought conditions. Moreover, the positive culture characteristics of tilapia are their tolerance to temperature fluctuation and salinity change. Disease-resistant fish species can play a critical role in adapting to climate change, as tilapia is a suitable fish that can resist most diseases and parasites.

For adaptation to climate change, tilapia farming is possible in a wide range of water environments, including freshwater, brackish water, and saltwater conditions. Tilapia can be produced under polyculture, monoculture, and integrated farming in pond systems, cage culture, pen culture, floodplain aquaculture, and coastal ponds. Since tilapia can easily survive in low water volume with high stocking density and short culture duration, this species can be cultured in seasonal water bodies. In addition, tilapia farming in rice fields can also adapt to changes in water level and temperatures. In fact, integrated rice–tilapia farming could be another adaptation strategy to reduce further risks of climate change. Moreover, tilapia can be cultured with brackish water species in coastal ponds as tilapia can tolerate moderate level of salinity. Ultimately, tilapia is a suitable aquaculture fish for current and future adaptation to climate change.

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