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Perceptions of the Impact of Climate Change on Performance of Fish Hatcheries in Bangladesh: An Empirical Study

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Abstract: The impacts of climate change (CC) on all spheres of human life are evident worldwide. Fish is the premier protein source, and its production in Bangladesh is mainly dependent on hatchery-based seed production. However, hatchery productivity is disrupted every year due to CC. This study assesses the impacts of CC on fish seed production in hatcheries from the perspective of hatchery owners. A semi-structured questionnaire survey was conducted with 60 hatchery owners in five sub-districts (Trishal, Mymensingh Sadar, Gouripur, Fulbaria, and Muktagacha) of the Mymensingh district, the highest aquaculture-producing zone in Bangladesh. Characteristically, hatchery owners are middle-aged and highly educated, with over a decade of experience in fish hatchery management. Likert scale results showed that hatchery owners concur with the evidence of CC, as seen by changes in air and water temperatures, rainfall, and sunlight intensity, as well as frequent natural disasters. Regression analysis showed that erratic rainfall, high temperature, and high solar radiation significantly influenced the hatchery owners' perceptions of CC. Principal component analysis (PCA) was used to divide the impact of CC into 12 components. Maximum variance (>70%) observed could be explained by problems related to embryonic and physiological development of fish fry, environmental changes, disease outbreaks, and poor growth of broodfish. The first PCA explained over 50% of the variances, with significantly higher factor loadings, comprising poor gonadal maturation, low hatching rate, poor egg and seed quality, low fecundity, and poor sperm quality of broodfish. The first PCA confirmed that the impacts of CC on fish hatchery operations were severe. Planting trees on the hatchery premises, aeration of brood ponds, increased water supply, and temperature control can be implemented to address the negative impacts on fish hatcheries. Further research in the laboratory and hatchery environments is needed.

Keywords: climate change; fish hatchery; seed production; aquaculture; Bangladesh

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1. Introduction

Globally aquaculture has grown faster than any other animal production sector [1], and Bangladesh is one of the leading fish-producing countries in the world, with an annual production of 4.62 million MT [2]. Aquaculture contributes to approximately 57.10% [2] of the total fish production in Bangladesh, thus becoming a promising sector for ensuring the food security for an ever-increasing population in Bangladesh and worldwide [3]. Over the past decade, aquaculture production in Bangladesh has increased 2.34 times [4]. However, this productivity is threatened by climate change (CC), which is the most critical and rapidly evolving global environmental issue [5]. Bangladesh is one of the most climate-vulnerable countries on Earth, with CC expected to have a broad impact across ecosystems, thus affecting livelihoods and food supplies, including fisheries and aquaculture [6–8]. Although aquaculture in Bangladesh was initiated using natural seed, it is now almost entirely replaced by hatchery-produced seed [4]. Currently, in Bangladesh, 935 private and 103 government hatcheries supply finfish seed, and 27 government and 50 private hatcheries also produce shrimp post-larvae [4]. Therefore, hatcheries are the primary suppliers of fish seeds in Bangladesh [9]. However, these enterprises are facing economic losses because of a decline in natural resources caused due to CC, habitat destruction, and the degradation of the ecological balance [9]. Fish production could be boosted by increased seed supply, which would improve the economic viability of hatcheries.

A hatchery is a multi-component system that requires close attention and various skills to run efficiently and profitably. A study reported that a late breeding season, lack of capital, limited technical knowledge of hatchery operation and management, poor transportation facilities, high transportation costs, high labor costs, limited training, and high spawn prices are major concerns for the effective operation of hatcheries [10]. Several biological concerns, such as improper broodstock selection, indiscriminate hybridization, and inbreeding, have also been raised [11]. In addition to these concerns, CC substantially impacts fish hatcheries [12]. Temperature is the variable that influences fish seed production the most, followed by rainfall, humidity, and solar radiation intensity [13–16]. Unfavorable temperature impairs growth by changing the metabolic and developmental processes of fishes [17–19], ultimately affecting seed production [20,21]. Rearing temperature considerably affects egg production, hatching rate, and larval growth rate [22–24]. The effects of water temperature on the growth and development of fish have been observed for many species, including *Oreochromis niloticus* [15], *Cyprinus carpio* [25], *Labeo rohita* [13], *Anguilla anguilla* [26], and *Takifugu obscurus* [27]. From a commercial point of view, farmed fish species in Bangladesh can be broadly divided into four categories such as carp (*Labeo rohita, Catla catla, Cirrhinus cirrhosus, Labeo calbasu, Labeo bata, Labeo gonius, Hypophthalmicthys molitrix, Aristichthys nobilis, Ctenopharyngodon idella, Cyprinus carpio*), catfish (*Pangasianodon hypophthalmus, Clarias batrachus, Heteropneoustes fossilis, Ompok pabda*), tilapia (*Oreochromis niloticus*), mainly being cultured in freshwater, and shellfish (*Penaeus monodon, Macrobrachium rosenbergii*), being cultured in coastal areas [28]. Hatchery-based seed production of all these species, except *C. carpio*, mainly occurs during the period from March to August, i.e., during summer when the temperature ranges from 25 to 28 °C. For this reason, there is a subtle relationship existing between temperature fluctuation and hatchery-based fish seed production. That is why hatchery production is almost stopped in winter compared to the warm season [22]. The readiness, maturity, and gonadal development of broodfish during the spawning season are impacted by temperature fluctuations, as well as irregular rainfall [29]. Faruk et al. [15] stated that feeding and growth rates are reduced at temperatures higher or lower than the optimum levels, and feeding and growth nearly stops at $\leq$20 °C. A more severe effect of CC is the weakening of the immune system of fishes, resulting in increased diseases, which ultimately hampers fish production [30,31]. Decreased fish production causes economic losses for hatchery owners, nursery operators, fry sellers, and other stakeholders of the fisheries sector [11]. Although cost-effective mitigation measures are difficult to implement in practice, researchers from several countries have identified ways to limit the climatic effect on hatcheries and fish farms [21,32]. Despite the difficulties in implementing cost-effective mitigation and adaptation methods, several studies have reported positive outcomes at fish farms and hatcheries. In this regard, Alam et al. [32] claimed that commercial fish hatcheries using a shed over the brood hapa (i.e., the rearing of fish in a closed net system in a pond or open water) during high-temperature months yielded a greater number of eggs. According to a perception study conducted by Adhikari et al. [21] in Andhra Pradesh, Karnataka, Gujarat, Odisha, and West Bengal states of India, fish farmers used fresh water from nearby surface or sub-surface sources to lower water temperature, oxygen tablets to supplement oxygen during the summer, and nets in pond dikes to prevent fish from escaping during flooding.

In Bangladesh, studies on the impact of CC at the hatchery level are limited, and farmers' perceptions and practical implications of CC on hatcheries remain undocumented. Moreover, participatory approaches including hatchery owners, farmers, traders, and government and non-government organizations have also been inconclusive [9]. Therefore, developing environmentally friendly solutions and considering farmers' perceptions could boost aquaculture production in Bangladesh. The main objective of this study was to reveal how hatchery owners perceive and confront the impact of CC on hatchery production and to recommend mitigation and adaptation practices for sustainable hatchery production in Bangladesh.

2. Materials and Methods

2.1. Site and Hatchery Selection

This study was conducted in five sub-districts (Upazilas) of Mymensingh district, namely, Trishal, Mymensingh Sadar, Gouripur, Fulbaria, and Muktagacha (Figure 1), based on their contribution to districts' national seed production. These Upazilas were selected because approximately 32% of hatcheries in Bangladesh are located in these regions [4,33]. Moreover, many private fish seed hatcheries in the study site possess appropriate agro-ecological conditions, namely, favorable climate, low-lying agricultural land, fertile soil, and abundant labor forces [34,35]. Population size data (complete list of hatcheries) from Upazila Fisheries Office, Department of Fisheries, Bangladesh, were considered to make the decision about number of hatcheries being surveyed in each Upazila. Before finalizing the sample size of hatcheries, the list of hatcheries collected from the UFO was validated with some lead hatchery owners applying key informant interview (KII) tool in each Upazila. From the entire list, 60 hatcheries that maintained regular production of fish seed commercially were randomly selected for this study. Final participation was based on ethical obligations, whereby hatchery owners consented to the use of their input for research purposes.

2.2. Data Collection

Hatchery owners were the preferred interviewees for data collection, owing to their technical capabilities for providing accurate answers. A questionnaire comprising two sections was developed for data collection. The questions in the first section were related to the demographic characteristics of the respondents, including name, age, gender, and education. The second section examined the primary purpose of the research, including the impact of CC on hatcheries, challenges, and mitigation strategies. The questionnaire was developed in a way that hatchery owners could understand and easily respond to. The draft questionnaire was pre-tested and validated by interviewing three respondents from each study site, followed by modifications based on respondent feedback. The final version of the questionnaire used for data collection was placed online via a Google form. In addition, data from the selected hatchery respondents were collected via face-to-face interviews from January to March 2021.

2.3. Data Analysis

The collected data were captured in MS Excel and rechecked to minimize errors. A brief descriptive statistical analysis was carried out to describe the general background of hatchery owners. Linear regression analysis was performed to assess the perceptions of hatchery owners on the impacts of CC. Principal component analysis (PCA) was undertaken to characterize the impacts of CC as perceived by hatchery owners, and to determine how hatchery owners' experiences challenge adapting to climate variability and whether they are isolated or clustered. The PCA equation is as follows:

$$PC_i = a_{1i}V_1 + a_{2i}V_2 \ldots\ldots\ldots\ldots\ldots a_{ni}V_n \tag{1}$$

where PC_i is the principal component i, and a_{ni} (n = 1 . . . n) is the loading (correlation coefficient) of the original variable V_n [36,37].

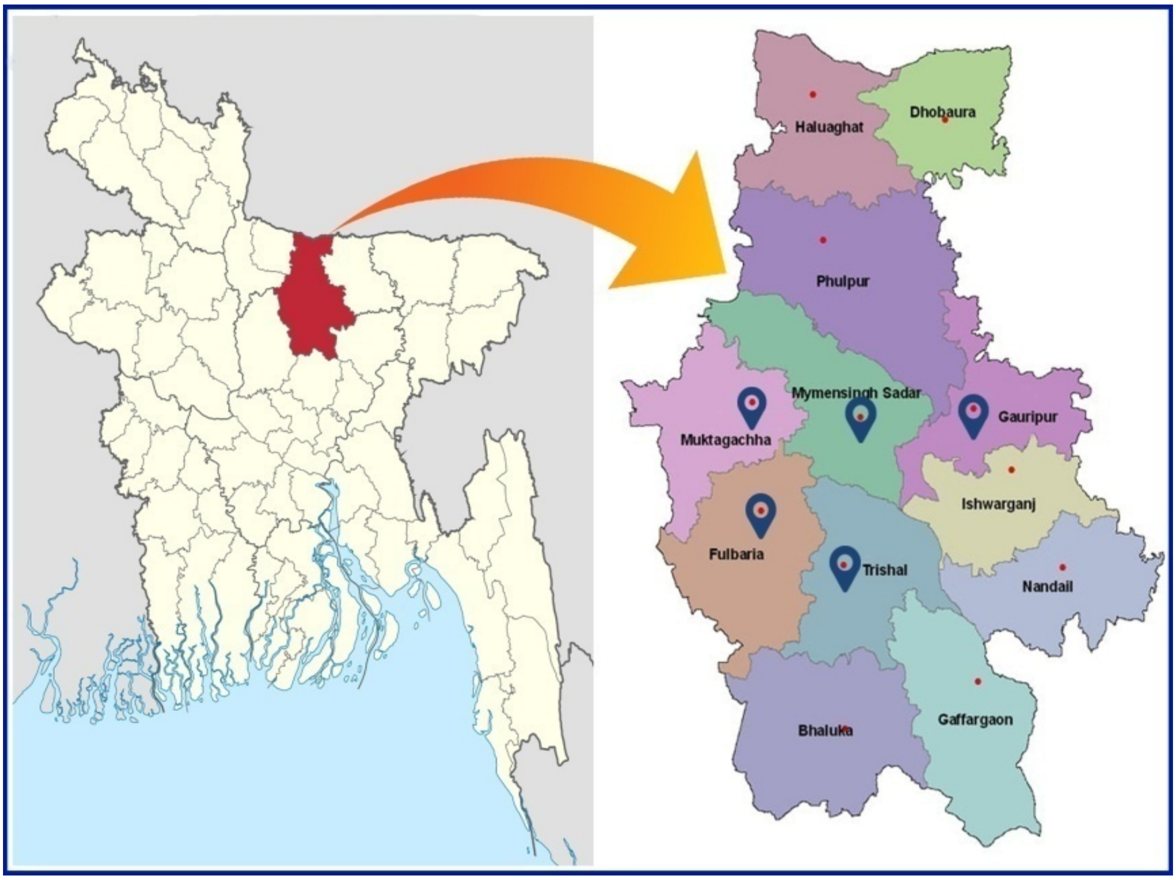

Figure 1. Study sites of the Mymensingh district.

A degree of subjectivity regarding the number of components was present in the PCA extraction. The standard stopping rule for determining the number of components is to stop when the eigenvalue drops below 1 because eigenvalues have standardized variances with mean 0 and standard deviation 1. Thus, components with an eigenvalue <1 are considered unimportant and were therefore excluded; however, components with an eigenvalue >1 are considered important and were therefore retained [38]. All statistical analyses were performed using the Statistical Package for Social Science (SPSS) 20 and Minitab 18.

3. Results

3.1. General Characteristics of Hatchery Owners

The hatchery owners in the study site were aged 15–65 years, with the majority falling within the middle age (31–50 years) category at 60%, followed by old age (51–65 years) category at 33.33%, and then young age (15–30 years) category at 6.67% (Table 1). Additionally, all hatchery owners were male, although female counterparts sometimes assisted in hatchery management. Among the respondents, 40% had completed class XI or higher, 38.33% had completed between class VI to X, 18% had completed between class I to V, and the remaining 1.67% were illiterate.

The majority (58.33%) of the hatcheries had been operating for 1–12 years, 30% for 13–24 years, and 11.67% for 25–36 years. Small hatcheries comprised 46.67%, medium hatcheries comprised 21.67%, and big hatcheries comprised 31.67% of the total hatcheries studied. Almost 51.67% of hatcheries had been producing commercial fish seed for at least ten years. All hatchery owners had received formal or informal training in hatchery operations for running their businesses efficiently. Moreover, upon answering a supplementary question, respondents indicated that they obtained information and skills through friends and relatives who had received official training from the Department of Fisheries, the Department of Youth Development, and non-governmental organizations.

Table 1. General characteristics of hatchery owners and hatcheries.

General Characteristics		Number	%
Age of hatchery owners	Young age (15–30)	4	6.67
	Middle age (31–50)	36	60.00
	Old age (51–65)	20	33.33
Gender	Male	60	100.00
	Female	0	0.00
Education	Illiterate	1	1.67
	Adult literacy/informal education	1	1.67
	Class I to V	11	18.33
	Class VI to X	23	38.33
	Class XI to above	24	40.00
Age of hatchery	1–12 Years	35	58.33
	13–24 Years	18	30.00
	25–36 Years	7	11.67
Size of hatchery	Small	28	46.67
	Medium	13	21.67
	Large	19	31.67
Year of fish production	1–5 Years	15	25.00
	6–10 Years	14	23.33
	Above 10 Years	31	51.67
Training experience	Yes	60	100.00
	No	0	0.00
Run other business	Yes	30	50.00
	No	30	50.00
Challenges face in the hatchery production	Yes	60	100.00
	No	0	0.00

3.2. Hatchery Owners' Perceptions of CC and Its Effects

As per hatchery owners' perceptions, 68.33% of respondents agreed with rising water temperature being the most evident effect of CC (Table 2). About 63% of respondents agreed with rising air temperature, and 45.76% of respondents agreed with natural calamities, including floods, cyclones, heavy rainfall, water logging, and flash flood, these being the next two important causes. Seven percent of respondents agreed that air temperature influenced pond water temperature.

Table 2. Hatchery owners' perceptions of climate change.

Perceptions of the Causes Responsible for Climate Change	Responses (%)				
	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Rising air temperature	6.67	63.33	30.00	0.00	0.00
Rising water temperature	6.67	68.33	25.00	0.00	0.00
Frequent natural calamities such as flood, cyclones, heavy rainfall, water logging, flash flood, etc.	1.69	45.76	52.54	0.00	0.00
Prolonged drought	0.00	22.03	76.27	1.69	0.00
River erosion	0.00	15.00	83.33	1.67	0.00
Rising sea level	0.00	35.00	63.33	1.67	0.00
Intense thunderstorm	0.00	21.67	76.67	1.67	0.00

3.3. Relationship between Hatchery Owners' Perceptions and Key Weather Parameters

Three weather variables, namely, erratic rainfall, high temperatures, and solar radiation, significantly influenced hatchery owners' perceptions of CC causes (Table 2). This was confirmed by the results of the Likert scale, where the values of multiple R and R-squared increased with the addition of independent variables from models 1 to 3 (Table 3). Approximately 27% of the variabilities were explained when erratic rainfall, high temperature, and solar radiation were considered together, as in the third model. The model showed a minimum error of the estimate and was highly statistically significant at the $p < 0.05$ probability level (Table 4).

Table 3. Model summary of the predictors.

Model Summary				
Model	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**
1	0.372 [a]	0.139	0.122	1.495
2	0.493 [b]	0.243	0.214	1.414
3	0.558 [c]	0.312	0.270	1.362

[a] Predictors: (Constant), Erratic rainfall; [b] Predictors: (Constant), Erratic rainfall, high temperature; [c] Predictors: (Constant), Erratic rainfall, high temperature, solar radiation.

Table 4. Analysis of Variance (ANOVA) of the regression model.

ANOVA [a]						
Model		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
1	Regression	18.680	1	18.680	8.363	0.006 [b]
	Residual	116.153	52	2.234		
	Total	134.833	53			
2	Regression	32.808	2	16.404	8.200	0.001 [c]
	Residual	102.026	51	2.001		
	Total	134.833	53			
3	Regression	42.024	3	14.008	7.547	0.000 [d]
	Residual	92.810	50	1.856		
	Total	134.833	53			

[a] Dependent Variable: Hatchery owners' perceptions on climate change; [b] Predictors: (Constant), Erratic rainfall; [c] Predictors: (Constant), Erratic rainfall, high temperature; [d] Predictors: (Constant), Erratic rainfall, high temperature, solar radiation.

3.4. Characteristics of CC Impacts on Fish Hatcheries

The PCA results (i.e., the rotated factor (varimax) matrix of independent variables with differential factor loadings) are summarized in Table 5. The first three principal components (PCs) explain 70.21% of the total variance and have Eigenvalues >1 (Table 5). The scree plot of all PCs is shown in Figure 2. The scree plot result of PCA extraction in SPSS, using a correlation matrix and standardized variables, indicated that factors are loaded and retained under three components. Moreover, in the PCA loading plot, three distinct clusters developed with three different types of variables (Figure 3). In this study, the content of each PC was best interpreted by examining the variables with factor loadings $\geq$0.5 (Figure 3).

Table 5. Eigenvalues of the correlation matrix.

Principal Component	Eigenvalue	Difference	Proportion (%)	Cumulative (%)
1	6.009	4.771	50.08	50.08
2	1.238	0.060	10.32	60.39
3	1.178	0.217	9.82	70.21
4	0.961	0.333	8.01	78.22
5	0.628	0.079	5.23	83.45
6	0.548	0.103	4.57	88.02
7	0.445	0.057	3.71	91.73
8	0.389	0.129	3.24	94.97
9	0.260	0.102	2.17	97.14
10	0.158	0.047	1.32	98.45
11	0.111	0.036	0.93	99.38
12	0.075	-	0.62	100.00

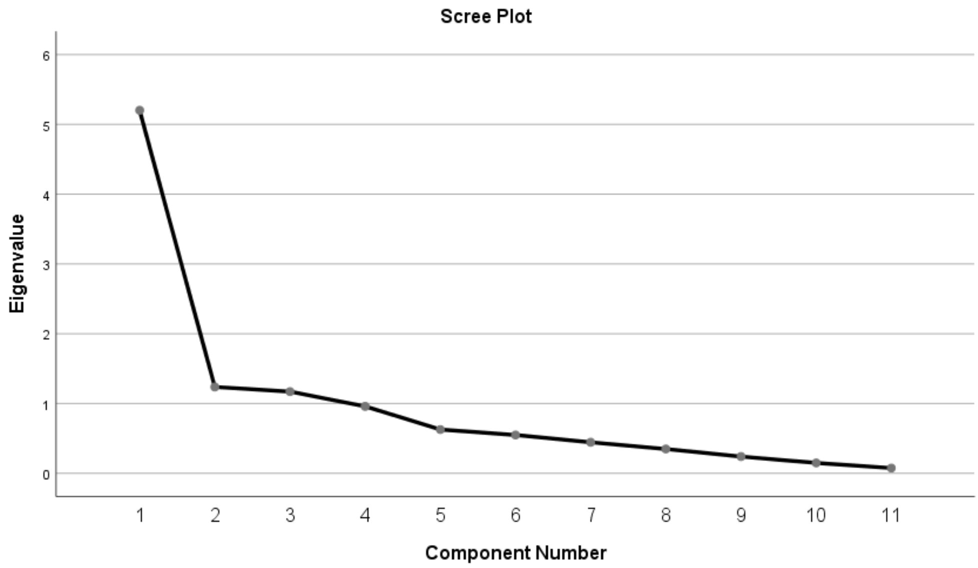

Figure 2. Scree plot (explained variance of each principal component) calculated for the factors.

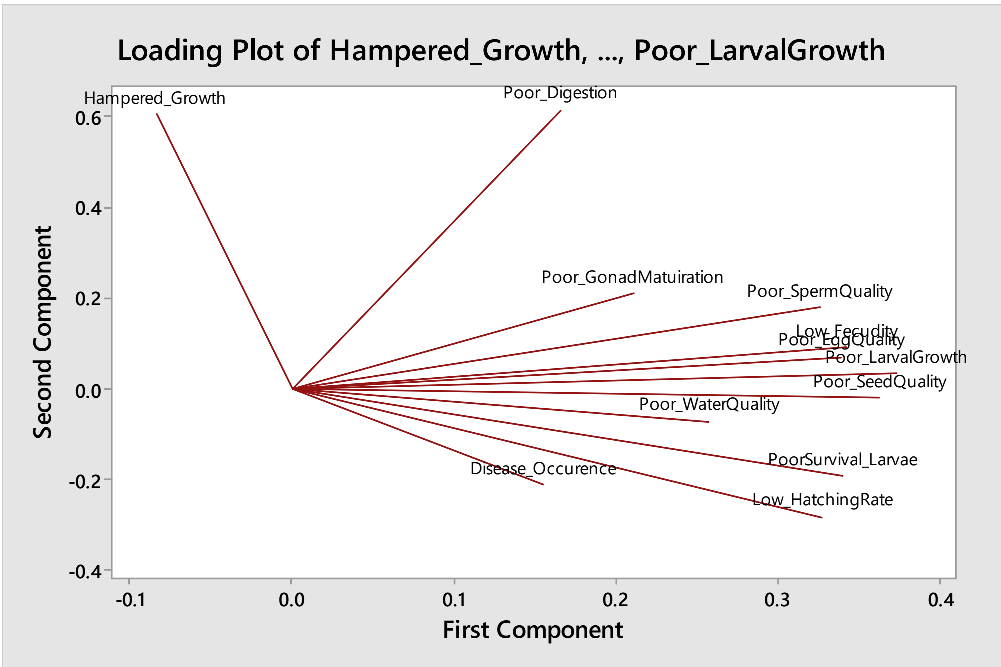

Figure 3. Loading plot corresponding to the top two principal components.

3.4.1. Component 1: Poor Reproductive Performance of Fish

The first PC, which indicates the orientation of poor reproductive performance, explained 50.08% of the variance and demonstrated higher positive correlations with poor larval growth; poor gonadal maturation; poor quality of eggs, seeds, and sperm; low hatching rate; and low fecundity (Table 6). These extracted components, either collectively or individually, had significant positive factor loadings. Individually, poor larval growth, with a positive correlation coefficient (0.874), contributed the most to this component, followed by poor gonadal maturation (0.861), low hatching rate (0.859), poor egg quality (0.849), poor seed quality (0.823), low fecundity (0.784), and poor sperm quality (0.736) (Table 6).

Table 6. Rotated component matrix and correlation coefficients of the variables with significant components for characterizing climate change impacts on fish hatchery operation.

Rotated Component Matrix [a]			
	Component		
	PC 1	PC 2	PC 3
Poor larval growth	0.874		
Poor gonadal maturation	0.861		
Low hatching rate	0.859		
Poor egg quality	0.849		
Poor seed quality	0.823		
Low fecundity	0.784		
Poor sperm quality	0.736		
Disease occurrence		0.810	
Poor survival of larvae		0.750	
Poor water quality		0.530	
Poor digestion			0.701
Hampered growth rate of broodstock			0.661

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. [a] Rotation converged in 4 iterations.

3.4.2. Component 2: Poor Survival in Relation to Disease and Poor Water Quality

The second PC was positively correlated with 10.32% of the variance and mainly correlated with disease occurrence (0.810), poor survival of larvae (0.750), and poor water quality (0.530) (Table 6).

3.4.3. Component 3: Poor Growth of Broodstock

The third PC indicated poor digestion and had a positive correlation coefficient (0.701). Similarly, the hampered growth rate of broodstock (0.661) displayed a positive correlation coefficient (Table 6).

3.5. Mitigation Measures as Perceived by Hatchery Owners

The hatchery owners gave their opinions on how the impacts of CC on hatcheries could be mitigated. Approximately 85% of hatchery owners suggested that planting trees around the hatchery could reduce overheating and keep the environment cool (Figure 4). Sixty eight percent hatchery owners suggested that aeration in broodfish ponds could increase dissolved oxygen levels in water. More than 60% of hatchery owners suggested maintaining tolerable water temperatures in nurseries or broodfish ponds through regular water changes or additional water supply. Around 57% of hatchery owners suggested the need for constructing temperature-controlled hatcheries to produce fry. Approximately 37% of hatchery owners suggested that oxygen tablets could be used to overcome low oxygen levels in the water. More than 30% of hatchery owners suggested raising the pond dikes to prevent flooding of hatchery ponds.

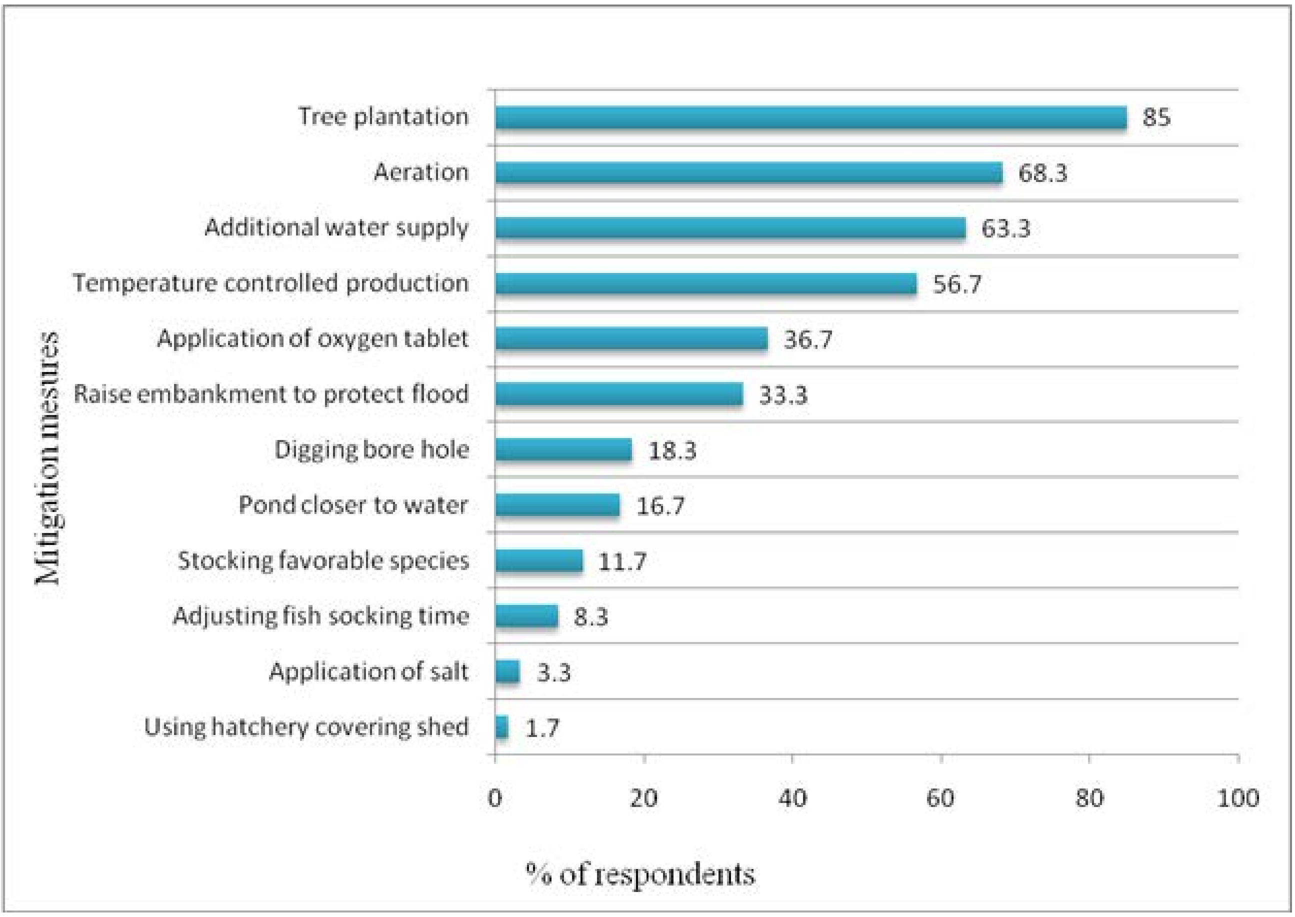

Figure 4. Responses of hatchery owners towards mitigation and adaptation to climate change.

4. Discussion

4.1. General Characteristics of Hatchery Owners

Although studies on the direct impact of CC on hatchery production in Bangladesh are limited, our findings related to general characteristics of hatchery owners are mostly consistent with those of other studies [39–41]. Most hatchery owners in Bangladesh are middle-aged, highly educated, have over ten years of experience, and are trained in fish hatchery management, which is consistent with the findings of Uddin et al. [42]. These hatchery owners continuously improve and modernize their operations to cope with CC and maintain the economic viability of their hatcheries.

In this study, most hatchery owners were middle-aged (31–50 years). Ali et al. [43] also reported that most fish farmers (>50%) in the Mymensingh district were aged between 31 and 40 years. Age groups vary depending on geographic regions within the country. For example, most hatchery owners (44%) in the Chandpur district were aged 41 to 60 years [39]. Pravakar et al. [39] reported that the age of fishermen in the Sundarbans ranged from 20 to 70 years, which is consistent with the current findings.

Approximately 40% of hatchery owners had a higher education than secondary school, which is important for improved hatchery management. In general, education can be essential in enabling farmers' technical understanding and approach to constraints [41] and ultimately efficient hatchery management. The literacy rate of respondents in this study was higher than the national adult literacy level of 65% [44]. According to Ali et al. [45], 50% of the fish farmers had completed SSC level education, and 22% had completed HSC level education. In Bagmara, Rajshahi district, Bangladesh, approximately 6% of respondents were illiterate, while 4% of respondents held a bachelor's degree. In contrast, Zaman et al. [46] found that 23.3% of fish farmers were illiterate, and 14.4, 8.9, and 6.7%

were educated up to the primary, secondary, and higher secondary levels, respectively. Tasnoova et al. [47] found that 60% of alternate-rice-fish farmers and 50% of rice-cum-fish farmers held a graduate degree or higher level of education. Pravakar et al. [39] stated that the level of education influenced the use of ponds for fish farming, which is consistent with the current findings.

All hatchery owners received either formal or informal training to run their businesses efficiently. Family members, friends, and relatives provided informal training, whereas the Department of Fisheries, the Department of Youth Development, and non-governmental organizations provided formal training. According to the respondents, the training enabled them to manage their hatchery activities effectively. Islam et al. [48] and Uddin et al. [42] reported effective management of fish farms by farmers who had received training. Approximately 50% of the hatchery owners earned income from other sources, such as fish culture, rice farming, cattle rearing, and poultry production. However, over recent years, hatchery owners have faced many unavoidable challenges, such as the impact of COVID-19, seed marketing problems, financial problems, and diseases during the production cycle [49].

4.2. Hatchery Owners' Perceptions on CC and Its Effects

All hatchery owners were professionals with extensive practical experience in hatchery management, and they agreed that the increasing water temperature was an effect of CC. Azad and Wadood [50] reported that high temperatures and erratic rainfall affect fish reproduction, growth, and migration patterns. Faruque and Kabir [51], in a case study of fish farmers in northwestern Bangladesh, claimed that the reduction in the overall total fish production was because of the decreased growth rate of cultured fish and increased fry and fingerling mortality caused by heat shock and diseases. As with fish farmers, fishermen perceived that the rise in temperature, frequency of tropical cyclones, and sea level, as well as the decrease in monsoon rainfall, had pronounced impacts on the declining fish population of the Bay of Bengal [52]. The findings of this study and the evidence included in the literature indicate that the perceptions held by hatchery owners on CC are realistic.

4.3. Relationship between Hatchery Owners' Perceptions and Key Weather Parameters

Hatchery owners depend heavily on nature for producing and sustaining their livelihoods. Therefore, they shared their views, potential abilities, and valuable knowledge through this survey, all of which were significant. Erratic rainfall, high temperatures, and solar radiation significantly influenced hatchery owners' perceptions of CC. According to a study in South Bengal, high temperatures, low rainfall, salinity intrusion, seasonal fluctuations, and prolonged droughts are the major effects of CC that affect pond fish farming [53]. Another study reported that aquaculture is vulnerable to several climatic factors, including global warming, rainfall variability, floods, droughts, temperature fluctuations, and salinity changes [54].

4.4. Characteristics of CC Impacts on Fish Hatcheries

4.4.1. Poor Reproductive Performance of Fish

The first PC addresses the adverse effects of CC on the embryonic and physiological development of fish fry, based on factor loadings. Poor larval growth had the highest loading, suggesting that larval growth of fishes was associated with favorable environmental conditions [55]. Several studies have highlighted that temperature has a strong influence on embryogenesis, hatching [24], and subsequent larval development, growth, and survival [56]. Moreover, temperature controls the physiological processes in fish, such as oxygen uptake rate, heart rate, locomotion, water balance, digestion, developmental rate, sex determination, and immune function [57]. Similarly, Aziz et al. [58] revealed that temperature strongly influences all physiological processes, particularly reproductive processes such as gamete development, ovulation and spermiation, spawning, embryogenesis, hatching, larval and juvenile development, and survival. Several reproductive functions, such as the gametogenesis and growth of larval and post-metamorphic individuals, are also temperature-dependent [59]. Extreme environmental temperatures affect the typical morphology of fish larvae, resulting in decreased egg, sperm, and seed quality [60]. Because fish are poikilotherms, changes in water temperature cause metabolic and developmental disorders, lowering larvae survival rates, reducing fecundity, and hampering gonadal maturation [56,61,62]. Additionally, incubation at temperatures below the optimum level delays embryo development, increasing disease susceptibility and reducing viability [63].

4.4.2. Poor Survival in Relation to Disease and Poor Water Quality

The disease occurrence and poor survival of larvae showed a positive correlation with CC, indicating that CC induces stress on fish larvae, thus leading to an increased susceptibility to disease, parasite infection, and death in fishes from hatcheries. Various studies have reported that the effects of CC are responsible for disease susceptibility in fishes [20,64,65]. Similar findings by Chiaramonte et al. [66] report that the increased susceptibility of fish larvae to pathogen attack caused by temperature change is a significant determinant of diseases, and is likely to be affected by direct and indirect thermal stressors. Harasawa et al. [67] reported that disease threats and invasive species induced by CC directly impact fish hatcheries. Rising water temperatures due to CC increase larval mortality in fishes [56]. Moreover, fish metabolism is directly related to surrounding water temperature, and changes in water temperature are known to affect their immune system [65]. Temperature fluctuation will likely accelerate the replication rate, virulence, life-cycle longevity, and transmission of pathogens among several fish species [68]. Additionally, CC is linked to water quality parameters because it gives rise to changes in the hydrology and hydrography of water systems [69]. The effect of CC has been described extensively, including the effect on water quality which disrupts host—pathogen interactions, sometimes creating beneficial conditions for pathogen amplification and spread or microbial and ecological dysbiosis [70–73]. Islam et al. [74] indicated that temperature fluctuation might be responsible for fish disease, water quality deterioration, oxygen deficiency in water, and larvae disfigurement. Ahmed and Diana [75] reported that changes in water temperature decrease primary productivity through water stratification and reduction in surface water nutrients. Furthermore, excessive heavy rainfall causes water turbidity, which reduces the growth of fish larvae by limiting sunlight penetration and hampering oxygen production [75]. Several studies showed the association of harmful algal bloom outbreaks with CC [76,77].

4.4.3. Poor Growth of Broodstock

Fish health, in terms of factors such as poor digestion and hampered growth rate of broodfish, has been positively linked to CC (Table 6). Abnormal fluctuations in water temperature causes loss of appetite in fish and larvae, and they stop feeding, which thus hinders their growth and development in hatcheries [19,78,79]. The effects of temperature on broodfish development, ovarian growth, egg production, and relative fecundity are profound [22]. The egg production capacity of broodfish decreases with the increase in water temperature [15]. Earlier studies observed maximal growth efficiency within a range of optimal water temperatures, with declining efficiency at both lower and higher temperatures [80]. Fang et al. [81] reported that water temperature directly impacts the activities of all enzymes, which in turn affect the digestibility and metabolism of nutrients such as proteins and lipids. In addition, the digestive processes and nutrient digestibility of fish larvae decreased at temperatures beyond the optimal range [82]. For example, fish feed more vigorously at higher water temperatures, and their digestive processes are accelerated [83]. In turn, cooler water temperatures reduce nutrient digestibility by reducing digestion rates, increasing gut transit time, and lowering gastrointestinal evacuation rates [84]. Furthermore, the metabolism and physiology, feeding behavior, and growth performance of fish are affected by prolonged temperature stress [68,85].

4.5. Mitigation Measures as Perceived by the Hatchery Owners

The impact of CC on hatchery productivity is multi-factorial and cost-effectively addressing its negative effects is challenging. In this study, most hatchery owners perceived that controlling water temperature and quality (Figure 4) are the prime mitigation and adaptation strategies. Fish farmers and hatchery owners have continued to produce fish for an extended period despite adverse climatic conditions. Hatchery-based seed production is critically impacted by climatic factors. As a result, fish hatchery seed production is impeded, affecting aquaculture productivity and resulting in economic losses. Sustainable mitigation strategies to combat poor climatic conditions have not been established yet in hatchery production and the aquaculture sector. The results of this survey revealed that farmers have observed benefits from implementing several mitigation measures and also highlighted that future mitigation measures, if cost-effective, could result in increased benefits. Farmers and hatchery owners are front-line stakeholders in fish production and have been attempting to adopt appropriate, cost-effective measures to tackle the adverse climatic conditions, as CC has a direct impact on fish farms and hatcheries. Several studies present cost-effective CC mitigation strategies for farms and fish hatcheries. Alam et al. [32] reported that commercial fish hatcheries should utilize cloth covered sheds for brood hapas to generate more eggs in the higher-temperature months. In addition, farmers pump freshwater into fish culture ponds to lower the temperature [21]. During the summer, several farmers use oxygen tablets in the ponds to increase the amount of oxygen in the water [32]. Adhikari et al. [32] reported that 60% of farmers maintain pond water levels by pumping water from boreholes, 48% used mesh-like structures in pond bunds to prevent fish from escaping in the event of flooding, and 16% used pumps to remove water. To operate their businesses, hatchery owners must be skilled in various areas to deal with increased technical issues. This study highlights this issue alongside other findings. Hemal et al. [10] reported that hatchery owners require more technical knowledge to run hatcheries effectively, and their capacity building is necessary for successfully producing hatchery-based seed and managing the related business.

According to Maulu et al. [20], mitigation and adaptation measures may help farming communities, ecosystems, and populations become more resilient to CC. Table 7 summarizes the existing mitigation techniques and future possible mitigation measures under adverse climatic conditions.

Table 7. Summary of the possible mitigation and adaptation measures under adverse climatic conditions as stated by hatchery owners.

Mitigation and Adaptation Strategies	Method	Timeframe	Impact
Increasing the inside air temperature	Use of polythene sheets to cover the hatchery	During the seed production cycle, when the temperature falls below the optimum	Positive
Maintaining favorable nursery and broodfish pond water temperature	Supply clean additional water to increase the volume of water in the hatchery tank and broodfish pond	If the seed and broodfish pond temperature exceeds tolerable limits.	Positive
Maintaining water oxygen levels	Use of a simple aerator system and oxygen tablets	If oxygen levels drop during hatchery seed production and pond broodfish management.	Positive
Preventing fish from escaping during seasonal floods	Repairing and raising pond dikes	In the dry season	Unknown
Creating a cool production environment	Suitable tree planting in pond dikes and the hatchery compound	In the wet season	Environmentally friendly hatchery compound

Several hatchery owners profited from implementing some of these mitigation measures; however, further research is needed to determine which mitigation practices and adaptation strategies are most suited for long-term hatchery seed production. Furthermore, to ensure sustainable output in the future, a long-term investigation of additional prospective mitigation techniques is required in laboratory and hatchery environments.

5. Conclusions

The overall findings of the present investigation showed that temperature, rainfall, and solar radiation influence hatchery productivity negatively. Therefore, the results of the present study on the perceptions of hatchery owners are appropriate and the most contextual in this regard. According to hatchery owners, the mitigation practices discussed in this study might have a positive impact on hatchery seed production, but the outcomes of several possible future mitigation measures are unknown. As a result, more laboratory and hatchery-based research is needed to increase hatchery seed production and sustainable aquaculture production under harsh climatic conditions.

6. New Insights

This paper investigated a different aspect from the perspective of hatchery owners on CC and expressed it in their language, which provides a new insight for readers.

Author Contributions: M.A.B.S.: introduction, methodology development, overall study and analysis of hatchery owners' perception, analysis and presentation of mitigation strategies, data curation, and writing the original draft. A.K.S.A.: concept development, investigation, supervision, editing the draft. B.M.: analysis of general characteristics, visualization, data curation, contributed to writing the original draft. M.M.A.: principal component analysis, related data analysis, writing—original draft. N.A.H.: concept development, investigation, data analysis, editing the draft. A.B.: concept development, investigation, data analysis, editing the draft. J.C.B.: fund acquisition, writing—review and editing. M.M.H.: conceptualization, abstract writing, validation, investigation, roles/writing—original draft; writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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References

1. Henriksson, P.J.G.; Zhang, W.; Nahid, S.A.A.; Newton, R.; Phan, L.T.; Dao, H.M.; Zhang, Z.; Jaithiang, J.; Andong, R.; Chaimanuskul, K.; et al. *Final LCA Case Study Report—Results of LCA Studies of Asian Aquaculture Systems for Tilapia, Catfish, Shrimp, and Freshwater Prawn*; Leiden University: Leiden, The Netherlands, 2014; Volume D 3.5, 165p.
2. DoF. *National Fish Week 2022 Compendium*; Department of Fisheries, Ministry of Fisheries and Livestock: Dhaka, Bangladesh, 2022; 160p. (In Bengali)
3. Alam, M.M.; Haque, M.M.; Aziz, S.B.; Mondol, M.M.R. Development of pangasius–carp polyculture in Bangladesh: Understanding farm characteristics by, and association between, socio-economic and biological variables. *Aquaculture* **2019**, *505*, 431–440. [CrossRef]
4. DoF. *Yearbook of Fisheries Statistics 2019–2020*; Fisheries Resources Survey System (FRSS), Department of Fisheries, Ministry of Fisheries and Livestock: Dhaka, Bangladesh, 2020; Volume 37, 141p.

5. Dutta, J.; Sen, T.; Mitra, A.; Zaman, S.; Mitra, A. Brief commentary on the impact of global climate change on fisheries and aquaculture with special reference to India. *Bangladesh J. Zool.* **2020**, *48*, 457–463. [CrossRef]
6. WorldFish Centre. *Global Vulnerability of Fisheries Systems to Climate Change*; ISSUES, Brief/1701; WorldFish Centre: Penang, Malaysia, 2007.
7. Haque, M.M.; Alam, M.R.; Alam, M.M.; Basak, B.; Sumi, K.R.; Belton, B.; Murshed-E-Jahan, K. Integrated floating cage aquageoponics system (IFCAS): An innovation in fish and vegetable production for shaded ponds in Bangladesh. *Aquac. Rep.* **2015**, *2*, 1–9. [CrossRef]
8. FAO. Climate Change Implications for Fisheries and Aquaculture. Summary of the findings of the IPCC Fifth Assessment Report. In *FAO Fisheries and Aquaculture Circular: Vol. FIAP/C1122*; Food and Agricultural Organization: Rome, Italy, 2016; 65p.
9. Parvez, M.S.; Rahman, M.A.; Hasan, M.J.; Rasel, M.S.E.; Shaikh, M.M.; Molla, M.H.R.; Chowdhury, S.H.; Billah, M.M. Role of Hatchery on Fish Seed Production in Patuakhali District of Bangladesh: An Overview. *Int. J. Chem. Environ. Biol. Sci.* **2018**, *6*, 1–7.
10. Hemal, S.; Uddin, M.S.; Uddin, M.S.; Majumdar, B.C.; Rasul, M.G.; Alam, M.T. Present status and problems of fish seed marketing in Sylhet district, Bangladesh. *Res. Agric. Livest. Fish.* **2017**, *4*, 45–54. [CrossRef]
11. Debnath, S.; Hossen, S.; Sharker, M.R.; Ghosh, A.; Ferdous, A.; Zannat, L.K.; Ali, M.M. Fish Seed Producing Hatcheries in Southern Bangladesh: An Overview. *Middle-East J. Sci. Res.* **2020**, *28*, 199–206.
12. Haque, M.M. Fisheries and Aquaculture in Seasonal Bangladesh: Implications of Climate Change. In *Impacts of Climate Change on Livelihoods, Agriculture and Aquaculture & Fisheries Sector of Bangladesh*; Wahab, M.A., Salam, M.A., Eds.; Department of Aquaculture, Bangladesh Agricultural University: Mymensingh, Bangladesh, 2009; pp. 47–53.
13. Kausar, R.; Salim, M. Effect of Water Temperature on the Growth Performance and Feed Conversion Ratio of *Labeo rohita*. *Pak. Vet. J.* **2006**, *26*, 105–108.
14. Khater, E.S.G.; Ali, S.A.; Mohamed, W.E. Effect of Water Temperature on Masculinization and Growth of Nile Tilapia Fish. *J. Aquac. Res. Dev.* **2017**, *8*, 8–12. [CrossRef]
15. Faruk, M.A.R.; Mausumi, M.I.; Anka, I.Z.; Hasan, M.M. Effects of temperature on the egg production and growth of monosex Nile Tilapia *Oreochromis niloticus* fry. *Bangladesh Res. Publ. J.* **2012**, *7*, 367–377.
16. Usman, I.; Auta, J.; Abdullahi, S.A. Effect of monthly variation in water temperature on artificial breeding of common carp (*Cyprinus carpio* L.) in Zaria, Nigeria. *Int. J. Fish. Aquat. Stud.* **2015**, *3*, 353–356.
17. Remen, M.; Nederlof, M.A.J.; Folkedal, O.; Thorsheim, G.; Sitjà-Bobadilla, A.; Pérez-Sánchez, J.; Oppedal, F.; Olsen, R.E. Effect of temperature on the metabolism, behaviour and oxygen requirements of *Sparus aurata*. *Aquac. Environ. Interact.* **2015**, *7*, 115–123. [CrossRef]
18. O'Gorman, E.J.; Ólafsson, Ó.P.; Demars, B.O.L.; Friberg, N.; Guðbergsson, G.; Hannesdóttir, E.R.; Jackson, M.C.; Johansson, L.S.; McLaughlin, Ó.B.; Ólafsson, J.S.; et al. Temperature effects on fish production across a natural thermal gradient. *Glob. Chang. Biol.* **2016**, *22*, 3206–3220. [CrossRef] [PubMed]
19. Mazumder, S.K.; De, M.; Mazlan, A.G.; Zaidi, C.C.; Rahim, S.M.; Simon, K.D. Impact of global climate change on fish growth, digestion and physiological status: Developing a hypothesis for cause and effect relationships. *J. Water Clim. Chang.* **2015**, *6*, 200–226. [CrossRef]
20. Maulu, S.; Hasimuna, O.J.; Haambiya, L.H.; Monde, C.; Musuka, C.G.; Makorwa, T.H.; Munganga, B.P.; Phiri, K.J.; Nsekanabo, J.D.M. Climate Change Effects on Aquaculture Production: Sustainability Implications, Mitigation, and Adaptations. *Front. Sustain. Food Syst.* **2021**, *5*, 609097. [CrossRef]
21. Adhikari, S.; Chaudhury, A.K.; Gangadhar, B.; Ramesh, R.; Mandal, R.N.; Sarosh, I.; Saha, G.S.; De, H.K.; Sivaraman, I.; Mahapatra, A.S.; et al. Adaptation and Mitigation Strategies of Climate Change Impact in Freshwater Aquaculture in some states of India. *J. FisheriesSciences.com* **2018**, *12*, 16–21.
22. Hossan, M.S.; Ulka, S.B.; Motin, M.A.; Tarafder, M.A.K.; Sukhan, Z.P.; Rashid, H. Egg and fry production performance of female tilapia related to fluctuating temperature and size variation. In Proceedings of the 4th the International Conference on Environmental Aspects of Bangladesh, Fukuoka, Japan, 24–25 August 2013; pp. 105–108.
23. Okunsebor, S.; Ofojekwu, P.; Kakwi, D.; Audu, B. Effect of Temperature on Fertilization, Hatching and Survival Rates of *Heterobranchus bidorsalis* Eggs and Hatchlings. *Br. J. Appl. Sci. Technol.* **2015**, *7*, 372–376. [CrossRef]
24. Valeta, J.S.; Likongwe, J.S.; Kassam, D.; Maluwa, A.O. Temperature-dependent egg development rates, hatchability and fry survival rate of Lake Malawi Tilapia (Chambo), *Oreochromis karongae* (Pisces: Cichlidae). *Int. J. Fish. Aquac.* **2013**, *5*, 55–59.
25. Hossain, M.I.; Khatun, M.; Kamal, B.M.M.; Habib, K.A.; Tumpa, A.S.; Subba, B.R.; Hossain, M.Y. Effects of Seasonal variation on Growth Performance of Mirror carp (*Cyprinus carpio* ver. specularis) in Earthen Nursery Ponds. *Our Nat.* **2015**, *12*, 8–18.
26. Politis, S.N.; Mazurais, D.; Servili, A.; Zambonino-Infante, J.L.; Miest, J.J.; Sørensen, S.R.; Tomkiewicz, J.; Butts, I.A.E. Temperature effects on gene expression and morphological development of European eel, *Anguilla anguilla* larvae. *PLoS ONE* **2017**, *12*, e0182726. [CrossRef]
27. Yoo, G.Y.; Lee, J.Y. The effect of feeding frequency, water temperature, and stocking density on the growth of river puffer *Takifugu obscurus* reared in a zero-exchange water system. *Fish. Aquat. Sci.* **2016**, *19*, 23. [CrossRef]
28. Parvin, G.A.; Fujita, K.; Matsuyama, A.; Shaw, R.; Sakamoto, M. Climate Change, Flood, Food Security and Human Health: Cross-Cutting Issues in Bangladesh. In *Food Security and Risk Reduction in Bangladesh*; Habiba, U., Hassan, A.W.R., Abedin, M.A., Shaw, R., Eds.; Springer: Berlin/Heidelberg, Germany, 2015; pp. 187–212.

29. Chowdhury, M.T.H.; Sukhan, Z.P.; Hannan, M.A. Climate change and its impact on fisheries resource in Bangladesh. In Proceedings of the International Conference on Environmental Aspects of Bangladesh (ICEAB10), Fukuoka, Japan, 4 September 2010; pp. 95–98.
30. Mallick, A.; Panigrahi, A.K. Effect of temperature variation on disease proliferation of common fishes in perspective of climate change. *Int. J. Exp. Res. Rev.* **2018**, *16*, 40–49. [CrossRef]
31. Islam, M.A.; Islam, M.S.; Wahab, M.A. Impacts of climate change on shrimp farming in the South-West coastal region of Bangladesh. *Res. Agric. Livest. Fish.* **2016**, *3*, 227–239. [CrossRef]
32. Alam, S.M.A.; Sarkar, M.S.I.; Miah, M.M.A.; Rashid, H. Management strategies for Nile Tilapia (*Oreochromis niloticus*) hatchery in the face of climate change induced rising temperature. *Aquac. Stud.* **2021**, *21*, 55–62. [CrossRef]
33. Hasan, N.A.; Heal, R.D.; Bashar, A.; Bablee, L.A.; Haque, M.M. Impacts of COVID-19 on the finfish aquaculture industry of Bangladesh: A case study. *Mar. Policy* **2021**, *130*, 104577. [CrossRef]
34. Ahmed, N.; Toufique, K. Greening the blue revolution of small-scale freshwater aquaculture in Mymensingh, Bangladesh. *Aquac. Res.* **2015**, *46*, 2305–2322. [CrossRef]
35. Alam, M.M.; Haque, M.M. Presence of antibacterial substances, nitrofuran metabolites and other chemicals in farmed pangasius and tilapia in Bangladesh: Probabilistic health risk assessment. *Toxicol. Rep.* **2021**, *8*, 248–257. [CrossRef]
36. Malinowski, R.M. *Factor Analysis in Chemistry*, 2nd ed.; Wiley: New York, NY, USA, 1991; 368p.
37. Statheropoulos, M.; Vassiliadis, N.; Pappa, A. Principal component and canonical correlation analysis for examining air pollution and meteorological data. *Atmos. Environ.* **1998**, *32*, 1087–1095. [CrossRef]
38. Mabe, F.N.; Donkoh, S.A.; Al-Hassan, S. Technology adoption typology and rice yield differentials in Ghana: Principal component analysis approach. *Afr. J. Sci. Technol. Innov. Dev.* **2019**, *11*, 555–567. [CrossRef]
39. Pravakar, P.; Sarker, B.S.; Rahman, M.; Hossain, M.B. Present Status of Fish Farming and Livelihood of Fish Farmers in Shahrasti Upazila of Chandpur District, Bangladesh. *Am.-Eurasian J. Agric. Environ. Sci.* **2013**, *13*, 391–397.
40. Khatun, S.; Adhikary, R.K.; Rahman, M.; Nurul, M.; Sikder, A.; Hossain, M.B. Socioeconomic Status of Pond Fish Farmers of Charbata, Noakhali, Bangladesh. *Int. J. Life Sci. Biotechnol. Pharma Res.* **2013**, *2*, 2–12.
41. Mithun, M.; Kowsari, M.; Sheheli, S. Socioeconomic characteristics and constraints of participatory pond fish farmers in Mymensingh district, Bangladesh. *Int. J. Agric. Res. Innov. Technol.* **2021**, *10*, 170–176. [CrossRef]
42. Uddin, M.N.; Kabir, K.H.; Roy, D.; Hasan, M.T.; Sarker, M.A.; Dunn, E.S. Understanding the constraints and its related factors in tilapia (*Oreochromis* sp.) fish culture at farm level: A case from Bangladesh. *Aquaculture* **2021**, *530*, 735927. [CrossRef]
43. Ali, H.; Azad, M.A.K.; Anisuzzaman, M.; Chowdhury, M.M.R.; Hoque, M.; Shariful, M.I. Livelihood status of the fish farmers in some selected areas of Tarakanda upazila of Mymensingh district. *J. Agrofor. Environ.* **2010**, *3*, 85–89.
44. BBS. *Statistical Yearbook of Bangladesh Bureau of Statistics*; Statistical Division, Ministry of Planning, Government of the People's Republic of Bangladesh: Dhaka, Bangladesh, 2002; 660p.
45. Ali, M.; Hossain, M.D.; Hasan, A.N.G.M.; Bashar, M.A. Assessment of the livelihood status of the fish farmers in some selected areas of Bagmara Upazilla under Rajshahi district. *J. Bangladesh Agric. Univ.* **2008**, *6*, 367–374. [CrossRef]
46. Zaman, T.; Jewel, M.A.S.; Bhuiyan, A.S. Present Status of Pond Fishery Resources and Livelihood of the Fish Farmers of Mohanpur Upazila in Rajshahi District. *Univ. J. Zool. Rajshahi Univ.* **2006**, *25*, 31–35. [CrossRef]
47. Tasnoova, S.; Iqbal, K.M.; Iwamoto, I.; Haque, M.M. Economic performance of fish-based farming systems in Bangladesh. *J. Fish. Aquat. Sci.* **2008**, *3*, 206–212. [CrossRef]
48. Islam, A.B.M.S.; Farouque, M.G.; Roy, D. Problem Confronted by the Fish Farmers in Practicing Semi-intensive climbing perch (*Anabus testubineus*) farming. *Bangladesh J. Ext. Educ.* **2013**, *25*, 53–61.
49. Rahman, M.A.; Alam, M.M.; Barman, S.K.; Hossain, M.J.; Tikadar, K.K. Effect of COVID-19 on Fisheries Products Exported from Southwest Bangladesh: A Case Study. *J. Bangladesh Agric. Univ.* **2022**, *20*, 217–224. [CrossRef]
50. Azad, A.K.; Wadood, S.N. *The Impact of Climate Change on Fish Production in Bangladesh: An Assessment*; Bureau of Economic Research (BER), University of Dhaka: Dhaka, Bangladesh, 2020. [CrossRef]
51. Faruque, M.H.; Kabir, M.A. Climate change effects on aquaculture: A case study from north western Bangladesh. *Int. J. Fish. Aquat. Stud.* **2016**, *4*, 550–556.
52. Alam, E.; Mallick, B. Climate change perceptions, impacts and adaptation practices of fishers in southeast Bangladesh coast. *Int. J. Clim. Chang. Strateg. Manag.* **2022**, *14*, 191–211. [CrossRef]
53. Halim, M.A.; Mondal, D.K.; Salam, M.A.; Hossain, M.S. Impacts of climate change on pond fish farming in Amtoli, Borguna, Bangladesh. *Int. J. Fish. Aquat. Stud.* **2017**, *5*, 38–41.
54. Rahman, M.L.; Shahjahan, M.; Ahmed, N. Tilapia farming in Bangladesh: Adaptation to climate change. *Sustainability* **2021**, *13*, 7657. [CrossRef]
55. McNamara, J.M.; Barta, Z.; Klaassen, M.; Bauer, S. Cues and the optimal timing of activities under environmental changes. *Ecol. Lett.* **2011**, *14*, 1183–1190. [CrossRef] [PubMed]
56. Pankhurst, N.W.; Munday, P.L. Effects of climate change on fish reproduction and early life history stages. *Mar. Freshw. Res.* **2011**, *62*, 1015–1026. [CrossRef]
57. Alfonso, S.; Gesto, M.; Sadoul, B. Temperature increases and its effects on fish stress physiology in the context of global warming. *J. Fish Biol.* **2021**, *98*, 1496–1508. [CrossRef]

58. Aziz, M.S.B.; Hasan, N.A.; Mondol, M.M.R.; Alam, M.M.; Haque, M.M. Decline in fish species diversity due to climatic and anthropogenic factors in HakalukiHaor, an ecologically critical wetland in northeast Bangladesh. *Heliyon* **2021**, *7*, e05861. [CrossRef]
59. Dastansara, N.; Vaissi, S.; Mosavi, J.; Sharifi, M. Impacts of temperature on growth, development and survival of larval *Bufo* (*Pseudepidalea*) *viridis* (Amphibia: Anura): Implications of climate change. *Zool. Ecol.* **2017**, *27*, 228–234. [CrossRef]
60. Pereira, B.F. Effect of Temperature on Sperm Motility in Fishes—A Review. *Int. J. Sci. Res. Methodol.* **2016**, *5*, 81–89.
61. Muchlisin, Z.A. A General Overview on Some Aspects of Fish Reproduction. *Aceh Int. J. Sci. Technol.* **2014**, *3*, 43–52. [CrossRef]
62. Karmakar, S.; Purkait, S.; Das, A.; Samanta, R.; Kumar, K. Climate change and inland fisheries: Impact and mitigation strategies. *J. Exp. Zool.* **2018**, *21*, 329–335.
63. Tucker, J.W. *Marine Fish Culture*; Springer: Boston, MA, USA, 1998; 750p. [CrossRef]
64. Stien, L.H.; Bracke, M.B.M.; Folkedal, O.; Nilsson, J.; Oppedal, F.; Torgersen, T.; Kittilsen, S.; Midtlyng, P.J.; Vindas, M.A.; Øverli, Ø. Salmon Welfare Index Model (SWIM 1.0): A semantic model for overall welfare assessment of caged Atlantic salmon: Review of the selected welfare indicators and model presentation. *Rev. Aquac.* **2013**, *5*, 33–57. [CrossRef]
65. Cascarano, M.C.; Stavrakidis-Zachou, O.; Mladineo, I.; Thompson, K.D.; Papandroulakis, N.; Katharios, P. Mediterranean Aquaculture in a Changing Climate: Temperature Effects on Pathogens and Diseases of Three Farmed Fish Species. *Pathogens* **2021**, *10*, 1205. [CrossRef] [PubMed]
66. Chiaramonte, L.; Munson, D.; Trushenski, J. Climate Change and Considerations for Fish Health and Fish Health Professionals. *Fisheries* **2016**, *41*, 396–399. [CrossRef]
67. Harasawa, H.; Matsuoka, Y.; Takahashi, K.; Hijioka, Y.; Shimada, Y.; Munesue, Y.; Lal, M. Potential Impacts of Global Climate Change. In *Climate Policy Assessment Asian-Pacific Integrated Modeling*; Kainuma, Y.M., Matsuoka, Y., Morita, T., Eds.; Springer: Berlin/Heidelberg, Germany, 2003; pp. 37–54.
68. Marcogliese, D.J. The impact of climate change on the parasites and infectious diseases of aquatic animals. *Rev. Sci. Tech.* **2008**, *27*, 467–484. [CrossRef]
69. Cochrane, K.; De Young, C.; Soto, D.T.; Bahri, D.T. *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge*; FAO Fisheries and Aquaculture Technical Paper No. 530; FAO: Rome, Italy, 2009.
70. Burge, C.A.; Eakin, C.M.; Friedman, C.S.; Froelich, B.; Hershberger, P.K.; Hofmann, E.E.; Petes, L.E.; Prager, K.C.; Weil, E.; Willis, B.L.; et al. Climate Change Influences on Marine Infectious Diseases: Implications for Management and Society. *Annu. Rev. Mar. Sci.* **2014**, *6*, 249–277. [CrossRef]
71. Harvell, C.D.; Mitchell, C.E.; Ward, J.R.; Altizer, S.; Dobson, A.P.; Ostfeld, R.S.; Samuel, M.D. Climate warming and disease risks for terrestrial and marine biota. *Science* **2002**, *296*, 2158–2162.
72. Altizer, S.; Ostfeld, R.S.; Johnson, P.T.; Kutz, S.; Harvell, C.D. Climate change and infectious diseases: From evidence to apredictive framework. *Science* **2013**, *341*, 514–519. [CrossRef]
73. Egan, S.; Gardiner, M. Microbial dysbiosis: Rethinking disease in marine ecosystems. *Front. Microbiol.* **2016**, *7*, 991. [CrossRef]
74. Islam, M.A.; Akber, M.A.; Ahmed, M.; Rahman, M.M.; Rahman, M.R. Climate change adaptations of shrimp farmers: A case study from southwest coastal Bangladesh. *Clim. Dev.* **2019**, *11*, 459–468. [CrossRef]
75. Ahmed, N.; Diana, J.S. Coastal to inland: Expansion of prawn farming for adaptation to climate change in Bangladesh. *Aquac. Rep.* **2015**, *2*, 67–76. [CrossRef]
76. Lafferty, K.D. The ecology of climate change and infectious diseases. *Ecology* **2009**, *90*, 888–900. [CrossRef] [PubMed]
77. Trainer, V.L.; Moore, S.K.; Hallegraeff, G.; Kudela, R.M.; Clement, A.; Mardones, J.I.; Cochlan, W.P. Pelagic harmful algal blooms and climate change: Lessons from nature's experiments with extremes. *Harmful Algae* **2019**, *91*, 101591. [CrossRef]
78. Shafland, P.L.; Pestrak, J.M. Lower lethal temperatures for fourteen non-native fishes in Florida. *Environ. Biol. Fishes* **1982**, *7*, 149–156. [CrossRef]
79. Ngoan, L.D. Effects of climate change in aquaculture: Case study in Thua Thien Hue Province, Vietnam. *Biomed. Int. J. Sci. Technol. Res.* **2018**, *10*, 7551–7552. [CrossRef]
80. Björnsson, B.; Tryggvadóttir, S.V. Effects of size on optimal temperature for growth and growth efficiency of immature Atlantic halibut (*Hippoglossus hippoglossus* L.). *Aquaculture* **1996**, *142*, 33–42. [CrossRef]
81. Fang, J.; Tian, X.; Dong, S. The influence of water temperature and ration on the growth, body composition and energy budget of tongue sole (*Cynoglossus semilaevis*). *Aquaculture* **2010**, *299*, 106–114. [CrossRef]
82. Amin, M.N.; Carter, C.G.; Barnes, R.S.K.; Adams, L.R. Protein and energy nutrition of brook trout (*Salvelinus fontinalis*) at optimal and elevated temperatures. *Aquac. Nutr.* **2016**, *22*, 527–540. [CrossRef]
83. Charo, H.K. Selection for Growth of Nile tilapia (*Oreochromis niloticus* L.) in Low Input Environments. Ph.D. Thesis, Wageningen University, Wageningen, The Netherlands, 2006.
84. Miegel, R.P.; Pain, S.J.; van Wettere, W.H.E.J.; Howarth, G.S.; Stone, D.A.J. Effect of water temperature on gut transit time, digestive enzyme activity and nutrient digestibility in yellowtail kingfish (*Seriola lalandi*). *Aquaculture* **2010**, *308*, 145–151. [CrossRef]
85. Lemasson, A.J.; Hall-Spencer, J.M.; Fletcher, S.; Provstgaard-Morys, S.; Knights, A.M. Indications of future performance of native and nonnative adult oysters under acidification and warming. *Mar. Environ. Res.* **2018**, *142*, 178–189. [CrossRef]