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Optimizing River Productivity: Comparative Insights into Ecological Integrity and Production Responses to River-Based Cage Fish Farming

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How To Cite: Ferdoushi, Z.; Hossain, R.; Hassan, K.M.T.H.; et al. Optimizing River Productivity: Comparative Insights into Ecological Integrity and Production Responses to River-Based Cage Fish Farming. *Aquatic Life and Ecosystems* **2026**, *2*(3), 12. <https://doi.org/10.53941/ale.2026.100012>

Received: 21 April 2026

Revised: 17 June 2026

Accepted: 26 June 2026

Published: 16 July 2026

Abstract: Cage culture systems in diverse aquatic habitats represent an emerging approach in aquaculture, but they face multiple challenges, including water quality management. The purpose of this study was to examine changes in biological and physicochemical water quality over 180 days in the Tangon River, Bangladesh, resulting from cage fish farming compared with open water. *Oreochromis niloticus* fingerlings were stocked in distinct cages with two diverse stocking densities (treatments): 25 fish/m³ (T I) and 35 fish/m³ (T II), while the non-cage farming site was treated as the control for the study. The study confirmed that the control and treatment sites had differing water quality. There were 67 different genera of plankton identified in the cages at the farming locations, compared to 44 at the control site. Cage farming site has a far higher total plankton count than the control site with total plankton mean values of $23.95 \pm 7.41 \times 10^3$ cells/L in cage farming sites and $20.82 \pm 7.00 \times 10^3$ cells/L in control sites. Cage farming sites exhibited higher mean plankton abundance than the control site; however, significant differences were detected primarily in Cyanophyceae, Copepoda and total zooplankton abundance, suggesting localized ecological responses rather than widespread ecosystem alteration. Overall, it was shown that Treatment I outperformed Treatment II in terms of fish biomass production and survival rate, suggesting that increased densities have a detrimental effect on growth.

Keywords: water quality; plankton; abundance; cage farm; distribution, growth

1. Introduction

The extensive network of rivers, floodplains, wetlands and inland water bodies makes Bangladesh one of the world's most important countries for inland fisheries and aquaculture production [1]. Productivity of inland open-water fisheries can be enhanced by the use of cage culture techniques [2]. Fish cage culture makes use of existing water supplies by enclosing fish in a container with free-flowing water, which encourages water exchange and waste elimination. One possible solution to the problem of insufficient supply of high-quality animal protein is to establish cage cultures in large bodies of water that are currently unused. Furthermore, the strategic use of the abundant water resources provides a means of livelihood to economically deprived fishermen of the surrounding communities in developing countries [3]. Cage-based fish farming has the potential to provide a steady supply of fish seed, making it an attractive option for structured fish seed production, especially in distant areas. Potential



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consequences of cage culture practices include alterations in plankton communities as well as sediment characteristics due to the accumulation of uneaten feed and fish wastes [4].

A variety of waterways in Bangladesh, including rivers, canals, oxbow lakes and haors, might be used as potential sites for cage culture [5]. River-based cage fish farming was implemented to support underprivileged people in Bangladesh. Thus, open water aquaculture provides several direct and indirect benefits for local people like high-quality protein production, employment and family income growth. Additionally, experiments have been conducted on cage culture with numerous freshwater species in Bangladesh. These include *Anabas testudineus*, *Clarias batrachus*, *Ompok pabda*, *Mystus cavasius* as well as *Oreochromis niloticus* [5]. Diversification with economically and regionally relevant species is needed to make cage cultivation more profitable and adoptable [6]. In recent years, fish cage farms have been seen as a potential means of enhancing fish variety conservation and population restoration [7]. Cage culture has grown fast in the last several decades because of many benefits, such as its low input-output ratio, ease of movement and maintenance and effective use of water resources. Alternatively, natural water bodies may suffer negative impacts of the cage culture on the environment [8]. These impacts are mainly associated with the accumulation of uneaten feed, fish feces and dissolved metabolic wastes excreted by fish, which may influence nutrient dynamics and surrounding aquatic communities [9]. However, this will also depend on the time over which they will release and the amount and the types of products [8]. In certain cases, waste products have the potential to boost primary production as well as the biodiversity of aquatic fauna. In addition, nutrient availability was found to control phytoplankton growth, biomass and species composition [10]. Nutrient inputs in the aquatic system may result in an increase in algal biomass, thus altering the ecosystem's function [11].

Although there has been a few studies on riverine cage fish cultivation in Bangladesh, the number is too small to be mentioned [12]. However, the ecological and environmental consequences of fish cage culture are poorly understood [11]. Under the above circumstances, this study is designed to investigate the effects of river-based cage fish farming by assessing the abundance and distribution of the planktonic community concerning some major physico-chemical parameters.

2. Materials and Methods

2.1. Study Area

The *Tangon* River of Bangladesh was selected for conducting the whole research work. This study was conducted in suspended cages on this river indicating a geographical position of 25°43'32" N and 88°26'02" E. When choosing the site for the cage farm, the proximity of the floodplain to the river and the resulting water flow were given major emphasis. Additionally, the selected site of the river was deeper than other sites, allowing for the maintenance of the ideal depth for cage fish farming. Two sampling points from the cage fish farming area and one sampling point from the non-farming area were selected for research purposes. The sampling point outside the cage farming area named as control was selected considering upstream of the cage site. Figure 1 illustrates the locations of the sampling sites used in this investigation.

2.2. Experimental Design with Cage Description

The cages used in the experiments were made of knotless polyethylene net with a mesh size of 2 cm. A cage structure constructed from galvanized iron (GI) pipes with a diameter of 1 inch supports the net cages with nylon ropes. Six cages (5 m × 3 m × 2 m) were chosen from established cages on the river and cages were arranged in three rows in the chosen site of the river. Each net cage had a volume of 30 m³ and was submerged at 2 m water depth. The six individual cages were stocked with *Oreochromis niloticus* fingerlings using two distinct stocking densities (treatments): 25 fish/m³ (T I), 35 fish/m³ (T II), and non-cage farming site treated as the control for the study. Each treatment has triplicate replications (n = 3). The six experimental cages were installed in the same river section characterized by continuous water exchange and relatively uniform flow conditions. To minimize potential interference among treatments and ensure water circulation, cages were arranged in three rows parallel to the direction of water flow. Adjacent cages were separated by approximately 3–5 m, and treatment groups were separated by approximately 8–10 m. This spacing was considered sufficient to reduce the influence of feed residues, fish metabolites and localized nutrient enrichment from neighboring cages. Based on the cage volume of 30 m³, each cage was initially stocked with 750 fish in T I and 1050 fish in T II. Fish growth and survival were monitored through periodic sampling, during which a representative number of fish were randomly collected from each cage and measured for body weight. At the end of the culture period, all fish from each cage were harvested, counted and weighed individually or in bulk to determine total harvest biomass. Net fish production, biomass gain and survival rate were calculated using standard aquaculture production formulas. Final biomass was estimated

from the total harvested weight of fish in each cage, while biomass gain was determined as the difference between final and initial biomass.

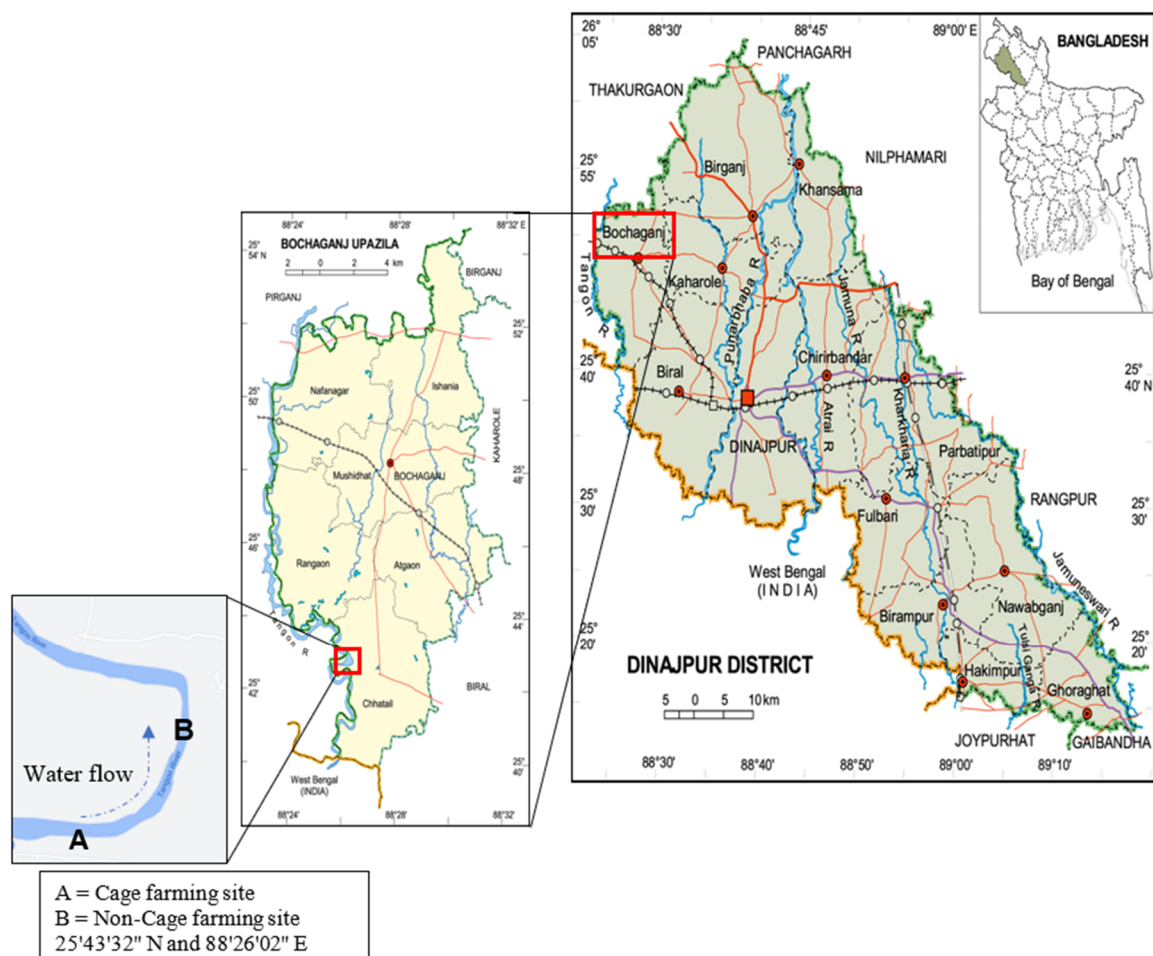


Figure 1. Map of the study area showing the sampling locations.

2.3. Sampling Duration

Samples were collected from each point fortnightly for six months from November 2020 to April 2021 because within this time *O. niloticus* got an appropriate time to attain marketable size. Field measurements of water quality indicators were taken and then the samples were transferred to the lab for further analysis. The collection of planktonic communities was done through direct sampling.

In the field, various physico-chemical parameters were measured, including water temperature, transparency, depth, pH, dissolved oxygen and total dissolved solids (TDS). The measurements were taken using various instruments, including thermometers, measuring scales, Secchi discs, dissolved oxygen meter (Model PDO-519, Lutron), pH meter (Model HI 98107, HANNA) and TDS meter (TDS-3). The total alkalinity was determined by collecting water samples from research sites and storing them in separate bottles that were properly leveled. The samples were then transported to the Fisheries Management laboratory of Hajee Mohammad Danesh Science and Technology University, Dinajpur. Total alkalinity was measured by titration method using 0.02 N sulfuric acid and methyl orange indicator [13].

2.4. Sample Collection and Preservation

At each of the sampling points, plankton samples were taken on a fortnightly basis. A plankton net with a fine mesh size was used to filter 20 L of water samples obtained at various depths from each site. The volume of the plankton samples was precisely measured after transferring the filtered sample into a measuring cylinder. Afterward, the plankton samples were placed in a 250 mL plastic bottle and kept in 5% buffered formalin for use in subsequent studies. A Sedgewick-Rafter counting cell was utilized to examine a 1 mL sub-sample from each preserved sample container under the illumination of an Olympus compound binocular microscope (Model B-2, including phase contrast capabilities).

2.5. Counting

The counting chamber of the Sedgewick-Rafter counting cell is 1 mL in capacity and is 50 mm in length, 20 mm in width and 1 mm in depth. With a capacity of 0.001 mL of each field, the counting chamber is split into a thousand equal sections. The planktonic organisms were counted in ten randomly selected fields of the slide.

2.6. Calculation

Calculation of plankton samples was done by using the following formula [14].

$$N = \frac{A \times 1000 \times C}{V \times F \times L}$$

where,

N = No. of plankton cells per liter of original water

A = No. of plankton counted

C = Volume of final concentrate of the sample in ml

V = Volume of a field in cubic mm

F = Number of fields counted

L = Volume of original water in liters

Identification of plankton was performed following APHA procedure [13]. Plankton abundance was measured and represented numerically per liter of water at each point.

2.7. CCA Biplot Analysis

Canonical Correspondence Analysis (CCA) was performed to evaluate the relationships between plankton community composition and measured environmental variables in the experimental cages and control site. For CCA analysis, at first the plankton genera included in the analysis are specified. Rare species occurring in less than 5% of the samples were excluded to minimize noise and improve model interpretation. Then, the environmental variables used in the ordination were examined and listed. CCA ordination biplots were generated to visualize relationships among plankton taxa, sampling stations, treatments and environmental variables while the variance explained by the first two canonical axes has been reported.

2.8. Statistical Analysis

The experimental data were analyzed using one-way analysis of variance (ANOVA), and Tukey's test was used to identify significant differences among the treatments ($p < 0.05$). The statistical analyses and CCA biplot analyses were executed by utilizing SPSS version 22 and PAST version 4 software, respectively. All statistical analyses of the study were found to be significant at 5% ($p < 0.05$).

3. Results

The water quality results obtained from both the farm and control sites were classified into two distinct categories, the physico-chemical section and the biological section which discovered the planktonic population inside the cage farming and non-farming sites in the river.

3.1. Physico-Chemical Parameters

Except for transparency, water temperature and water depth, the mean values of the physico-chemical parameters recorded at the control site were generally lower than those at the farmed site. Table 1 displays the mean ($\pm$ SD) values of the physico-chemical parameters of the study area as measured fortnightly by the current study every two weeks where significant differences were observed only for nitrate and ammonia.

Table 1. Mean values ($\pm$ SD) of physico-chemical parameters of water in three sampling sites during study period.

Parameters	Sampling Sites			F-Value	Level of Significance
	Treatment I	Treatment II	Control		
Air temperature ($^{\circ}$ C)	23.26 $\pm$ 3.66 (18.37–29.60)	23.83 $\pm$ 3.70 (18.67–30.07)	23.99 $\pm$ 4.08 (19.60–32.30)	0.120	NS
Water temperature ($^{\circ}$ C)	22.83 $\pm$ 3.89 (18.10–29.67)	23.38 $\pm$ 3.80 (18.27–30.00)	23.32 $\pm$ 3.92 (18.10–30.50)	0.069	NS
Water level (m)	2.91 $\pm$ 0.62 (2.22–4.10)	2.99 $\pm$ 0.63 (2.07–4.02)	3.04 $\pm$ 0.62 (2.19–4.03)	0.132	NS
Transparency (cm)	62.06 $\pm$ 8.54 (44.77–76.33)	61.39 $\pm$ 8.68 (45.33–71.33)	65.60 $\pm$ 8.82 (47.87–78.67)	0.870	NS
Dissolved oxygen (mg/L)	7.74 $\pm$ 1.07 (6.30–9.37)	7.31 $\pm$ 0.83 (5.90–8.67)	7.35 $\pm$ 0.60 (6.27–8.20)	1.194	NS
pH	7.79 $\pm$ 0.55 (6.67–8.70)	7.65 $\pm$ 0.51 (6.77–8.53)	7.50 $\pm$ 0.36 (6.83–7.83)	1.195	NS
Total dissolved solid (mg/L)	71.08 $\pm$ 5.27 (62.00–79.33)	69.11 $\pm$ 6.15 (59.67–77.33)	70.14 $\pm$ 5.79 (60.33–76.33)	0.250	NS
Nitrate (mg/L)	0.15 $\pm$ 0.25 (0–0.75)	0.10 $\pm$ 0.20 (0–0.58)	0.02 $\pm$ 0.07 (0–0.25)	1.342	*
Phosphate (mg/L)	2.61 $\pm$ 1.61 (1.00–4.00)	3.17 $\pm$ 1.52 (1.00–4.00)	2.25 $\pm$ 1.65 (0.67–5.00)	1.646	NS
Ammonia (mg/L)	0.15 $\pm$ 2.2 (0–0.25)	0.24 $\pm$ 1.33 (0–2.67)	0.08 $\pm$ 0.00 (0–0.25)	0.930	**
Total Alkalinity (mg/L)	70.0 $\pm$ 10.0 (58.67–88.67)	70.92 $\pm$ 12.80 (52.00–92.00)	67.11 $\pm$ 10.71 (56.00–84.67)	0.367	NS

NS = Values are not significantly different ($p > 0.05$). * Values indicate a significant difference at 5% significance level based on one-way ANOVA followed by Tukey's test. ** Values indicate a significant difference at 1% significance level based on one-way ANOVA followed by Tukey's test.

3.2. Qualitative Study of Plankton Community

A total of 50 genera of phytoplankton were found that belong to 4 groups such as Euglenophyceae, consisting of 2 genera, Cyanophyceae consisting of 7 genera, Bacillariophyceae consisting of 16 genera and Chlorophyceae consisting of 25 genera (Figure 2). Among zooplankton, 17 genera were identified, among these Copepoda composed of 2 genera, Rotifera 8 genera, Cladocera consisting of 6 genera and Crustacea with 1 genus (Figure 2). A comprehensive list of plankton groups recognized across different sampling sites, highlighting spatial variations in community composition is listed in Table 2.

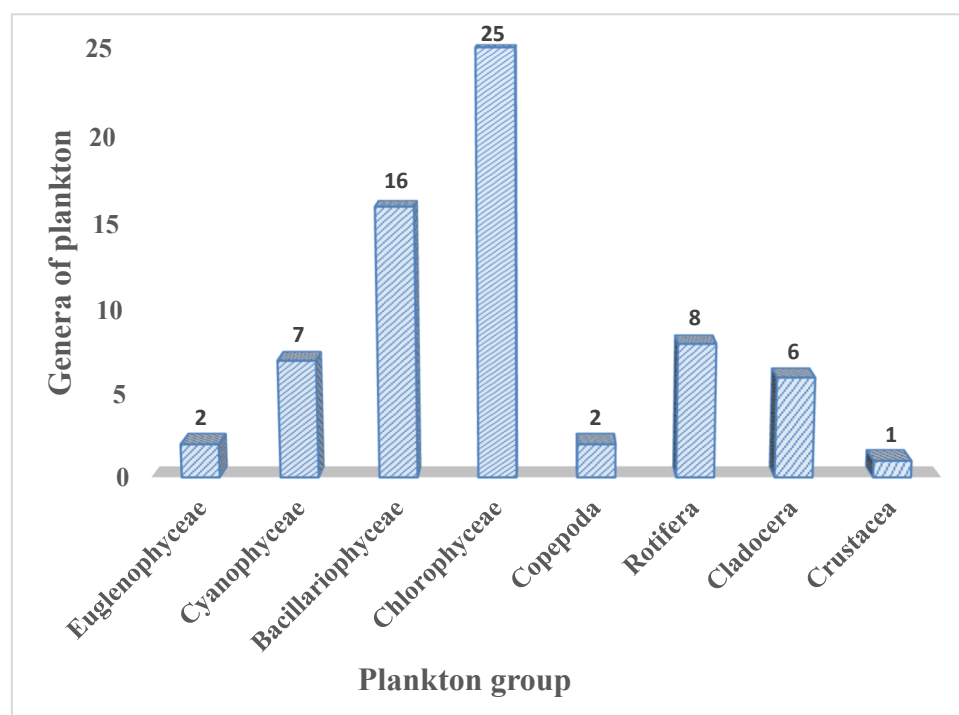
**Figure 2.** Plankton genera composition.

Table 2. List of groups of plankton identified in different sampling sites.

Plankton Types	Groups	Taxa in Treatment (Cage Farming Sites)	Taxa in Control (Non-Cage Farming Sites)
Phytoplankton	Bacillariophyceae	<i>Asterionella</i> , <i>Aulacoseira</i> , <i>Amphora</i> , <i>Cymbella</i> , <i>Cyclotella</i> , <i>Diatom</i> , <i>Fragillaria</i> , <i>Gomphonema</i> , <i>Melosira</i> , <i>Nitzschia</i> , <i>Navicula</i> , <i>Pinnularia</i> , <i>Synedra</i> , <i>Surirella</i> , <i>Tabellaria</i> , <i>Thalassiothrix</i>	<i>Asterionella</i> , <i>Cyclotella</i> , <i>Diatom</i> , <i>Fragillaria</i> , <i>Melosira</i> , <i>Navicula</i> , <i>Synedra</i> , <i>Surirella</i> , <i>Tabellaria</i> , <i>Thalassiothrix</i>
	Chlorophyceae	<i>Botryococcus</i> , <i>Chlorella</i> , <i>Chlamydomonas</i> , <i>Cladophora</i> , <i>Coelastrum</i> , <i>Ceratium</i> , <i>Euastrum</i> , <i>Eudorina</i> , <i>Hydrodictyon</i> , <i>Mesotaenium</i> , <i>Microspora</i> , <i>Oedogonium</i> , <i>Oocystis</i> , <i>Penium</i> , <i>Pediastrum</i> , <i>Pandorina</i> , <i>Planktosphaerina</i> , <i>Staurostrum</i> , <i>Spirogyra</i> , <i>Sparocystis</i> , <i>Scenedesmus</i> , <i>Stigeoclonium</i> , <i>Tetraspora</i> , <i>Volvox</i> , <i>Zygnema</i>	<i>Chlorella</i> , <i>Chlamydomonas</i> , <i>Cladophora</i> , <i>Coelastrum</i> , <i>Ceratium</i> , <i>Hydrodictyon</i> , <i>Microspora</i> , <i>Oedogonium</i> , <i>Penium</i> , <i>Pediastrum</i> , <i>Planktosphaerina</i> , <i>Volvox</i> , <i>Zygnema</i>
	Cyanophyceae	<i>Aphanocapsa</i> , <i>Aphanothece</i> , <i>Aphanizomenon</i> , <i>Anabaena</i> , <i>Microcystis</i> , <i>Nostoc</i> , <i>Oscillatoria</i>	<i>Aphanothece</i> , <i>Aphanizomenon</i> , <i>Anabaena</i> , <i>Microcystis</i> , <i>Nostoc</i> , <i>Oscillatoria</i>
	Euglenophyceae	<i>Euglena</i> , <i>Phacus</i>	<i>Euglena</i> , <i>Phacus</i>
	Copepoda	<i>Diaptomus</i> , <i>Cyclops</i>	<i>Diaptomus</i> , <i>Cyclops</i>
Zooplankton	Cladocera	<i>Bosmina</i> , <i>Ceriodaphnia</i> , <i>Daphnia</i> , <i>Diaphanosoma</i> , <i>Moina</i> , <i>Sida</i>	<i>Daphnia</i> , <i>Diaphanosoma</i> , <i>Moina</i> , <i>Sida</i>
	Rotifera	<i>Asplanchna</i> , <i>Brachionus</i> , <i>Keratella</i> , <i>Lecane</i> , <i>Monostyla</i> , <i>Notholca</i> , <i>Pompholyx</i> , <i>Trichocerca</i>	<i>Asplanchna</i> , <i>Brachionus</i> , <i>Keratella</i> , <i>Lecane</i> , <i>Monostyla</i> , <i>Pompholyx</i>
	Crustacean larvae	<i>Nauplius</i>	<i>Nauplius</i>

3.3. Quantitative Abundance of Plankton Community

Chlorophyceae and Bacillariophyceae were found as the dominant groups of phytoplankton while Copepoda was the dominant group among the zooplankton (Table 3). Among phytoplankton groups, Cyanophyceae abundance differed significantly among sampling sites ($p < 0.01$), with higher mean values recorded in the cage-farming treatments than in the control site. Similarly, Copepoda abundance were significantly greater in cage-farming areas than in the control site ($p < 0.05$). In contrast, Euglenophyceae, Bacillariophyceae, Chlorophyceae, Cladocera, Rotifera, total phytoplankton and total plankton abundance showed no significant differences among sampling sites ($p > 0.05$).

Table 3. Mean values ($\pm$ SD) and ranges of plankton ($\times 10^3$ cells/L) in three sampling sites during study period.

Plankton Groups	Sampling Sites			F-Value	Level of Significant
	Treatment I	Treatment II	Control		
Euglenophyceae	0.84 $\pm$ 0.40 (0.32–2.30)	0.77 $\pm$ 0.38 (0.29–1.84)	0.73 $\pm$ 0.40 (0.26–1.84)	0.73	NS
Bacillariophyceae	7.78 $\pm$ 03.03 (3.22–13.32)	7.89 $\pm$ 03.16 (3.68–14.26)	7.14 $\pm$ 2.92 (2.76–14.26)	0.64	NS
Cyanophyceae	1.90 $\pm$ 0.90 (0.46–3.68)	2.08 $\pm$ 0.80 (0.92–4.14)	1.45 $\pm$ 0.73 (0.43–3.22)	5.625	**
Chlorophyceae	6.41 $\pm$ 3.12 (1.38–11.40)	6.33 $\pm$ 3.10 (1.38–11.96)	5.72 $\pm$ 02.73 (0.92–10.58)	0.572	NS
Copepoda	2.75 $\pm$ 0.93 (0.92–5.06)	2.70 $\pm$ 0.66 (1.38–4.14)	1.94 $\pm$ 0.63 (0.46–3.22)	13.149	*
Cladocera	1.32 $\pm$ 0.53 (0.34–2.30)	1.17 $\pm$ 0.49 (0.46–2.76)	1.06 $\pm$ 0.56 (0.39–2.30)	2.279	NS
Rotifera	2.00 $\pm$ 1.01 (0.29–4.14)	2.10 $\pm$ 0.86 (0.46–3.68)	1.95 $\pm$ 0.92 (0.38–3.68)	0.233	NS
Crustacean Larvae	0.85 $\pm$ 0.49 (0.30–1.84)	0.87 $\pm$ 0.40 (0.33–1.84)	0.78 $\pm$ 0.38 (0.26–1.84)	0.420	NS

NS = Values are not significantly different ($p > 0.05$). * Values indicate a significant difference at 5% significance level based on one-way ANOVA followed by Tukey's test. ** Values indicate a significant difference at 1% significance level based on one-way ANOVA followed by Tukey's test.

The cage-farming sites generally supported higher plankton abundance and diversity than the non-farmed control site. A total of 67 plankton genera were recorded in cage-farming areas compared with 44 genera in the control site. The mean value ($\pm$ SD) of total phytoplankton fluctuated as $16.92 \pm 6.14 \times 10^3$ cells/L,

$17.08 \pm 6.26 \times 10^3$ cells/L and $15.05 \pm 5.92 \times 10^3$ cells/L in Treatment I, Treatment II and Control, respectively (Table 4). The dominant groups of zooplankton were Rotifera and Copepoda, while the differences of mean total zooplankton abundance varied significantly ($p < 0.01$). Mean total plankton abundance was also higher in the cage-farming sites ($23.86 \pm 7.22 \times 10^3$ cells/L in Treatment I and $23.95 \pm 7.41 \times 10^3$ cells/L in Treatment II) than in the control site as $20.82 \pm 7.00 \times 10^3$ cells/L (Table 4). However, these differences were not statistically significant ($p > 0.05$). The monthly variation of total plankton at three sampling sites reported that the abundance of plankton decreased gradually with the rising water temperature (Figure 3). These results indicate that cage farming was associated with increases in specific nutrient-sensitive plankton groups and total zooplankton abundance, whereas broader changes in overall plankton abundance and community structure were limited during the study period.

Table 4. Mean $\pm$ SD total plankton ($\times 10^3$ cells/L) in the sampling sites during the sampling period.

Parameters	Sampling Sites			F-Value	Level of Significant
	Treatment I	Treatment II	Control		
Total					
Phytoplankton	16.92 ± 6.14	17.08 ± 6.26	15.05 ± 5.92	1.191	NS
Total Zooplankton	6.93 ± 1.57	6.86 ± 1.29	5.76 ± 1.37	7.677	**
Total Plankton	23.86 ± 7.22	23.95 ± 7.41	20.82 ± 7.00	2.194	NS

NS = Values are not significantly different ($p > 0.05$). ** Values indicate a significant difference at 1% significance level based on one-way ANOVA followed by Tukey's test.

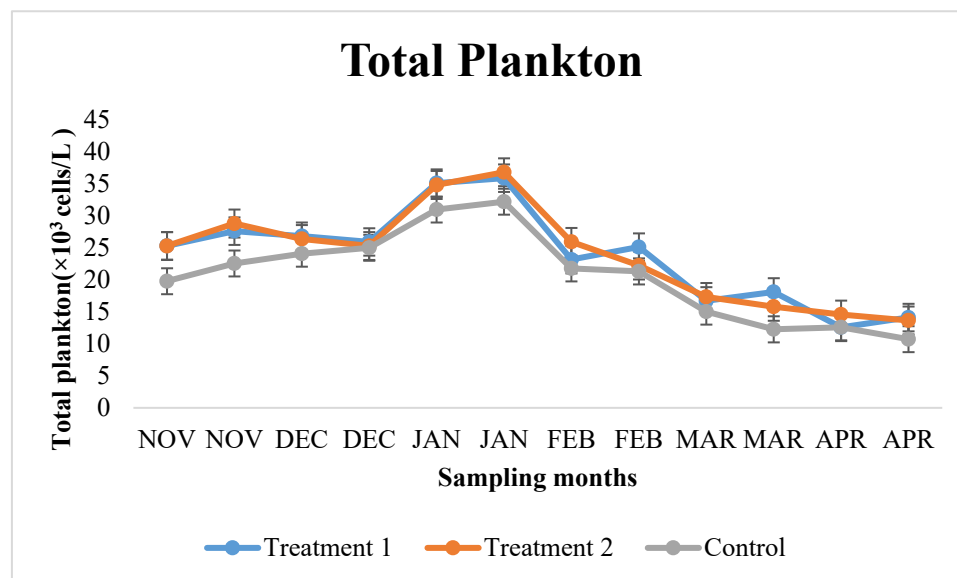


Figure 3. Monthly variation of total plankton at three sampling sites.

3.4. The Beneficial and Potentially Harmful Plankton Community

Among different beneficial groups of plankton, Chlorophyceae was recorded as the dominant plankton group in the farming area which provided a beneficial role in the river-based cage culture area (Table 5). Meanwhile, Cyanophyceae and Euglenophyceae abundance were found to be higher in the treatments than in the control site due to the accumulation of nitrogen and phosphorus from the supplementary feed provided in the farming area.

Among beneficial plankton, *Diatom* and *Cyclotella* of Bacillariophyceae group are the highest and lowest abundance of phytoplankton with 729 and 14 individuals/L in the cage and non-cage farming area, respectively (Table 5). Meanwhile, *Euglena* is a genus of harmful phytoplankton with the highest abundance of 219 individuals/L in cage farming areas, and the lowest abundance of *Phacus* is found in non-cage farming area with only 10 individuals/L. About 82% of phytoplankton found in the study site were beneficial for farming purposes while 18% of phytoplankton was identified as harmful for farming (Figure 4).

Table 5. Abundance of plankton in cage farming and non-cage farming sites.

Groups	Genera	Abundance in Cage Farming Sites	Abundance in Non-Cage Farming Site
Beneficial Planktons	<i>Asterionella</i>	++	++
	<i>Aulacoseira</i>	++	–
	<i>Amphora</i>	+	–
	<i>Cymbella</i>	+	–
	<i>Cyclotella</i>	++	+
	<i>Diatom</i>	+++	+++
	<i>Fragillaria</i>	+++	+++
	<i>Gomphonema</i>	+	–
	<i>Melosira</i>	+++	++
	<i>Nitzschia</i>	+	–
	<i>Navicula</i>	+	+++
	<i>Pinnularia</i>	+	–
	<i>Synedra</i>	+++	+++
	<i>Surirella</i>	+	+
	<i>Tabellaria</i>	+++	+++
	<i>Thalassiothrix</i>	++	++
	<i>Botryococcus</i>	++	–
	<i>Chlorella</i>	+++	+++
	<i>Chlamydomonas</i>	++	++
	<i>Cladophora</i>	++	++
	<i>Coelastrum</i>	++	++
	<i>Ceratium</i>	++	++
	<i>Euastrum</i>	+	–
	<i>Eudorina</i>	+	–
	<i>Hydrodictyon</i>	+++	+++
	<i>Mesotaenium</i>	+	–
	<i>Microspora</i>	+++	+++
	<i>Oedogonium</i>	++	++
	<i>Oocystis</i>	+	–
	<i>Penium</i>	++	++
	<i>Pediastrum</i>	++	++
	<i>Pandorina</i>	+	–
	<i>Planktosphaerina</i>	++	++
Potentially Harmful Planktons	<i>Staurastrum</i>	+	–
	<i>Spirogyra</i>	+	–
	<i>Sparocystis</i>	+	–
	<i>Scenedesmus</i>	+	–
	<i>Stigeoclonium</i>	+	–
	<i>Tetraspora</i>	+	–
	<i>Volvox</i>	++	++
	<i>Zygnema</i>	++	++
	<i>Aphanocapsa</i>	+	–
	<i>Aphanothece</i>	++	++
	<i>Aphanizomenon</i>	++	++
	<i>Anabaena</i>	++	++
Cyanophyceae	<i>Microcystis</i>	+++	+++
	<i>Nostoc</i>	++	++
	<i>Oscillatoria</i>	+++	+++
Euglenophyceae	<i>Euglena</i>	+++	+++
	<i>Phacus</i>	+	+

–: Absent, +: Rare, ++: Common, +++: Dominant. Note: (–): 0 ind./L; (+): 1–50 ind./L; (++) : 51–100 ind./L; (+++): >100 ind./L.

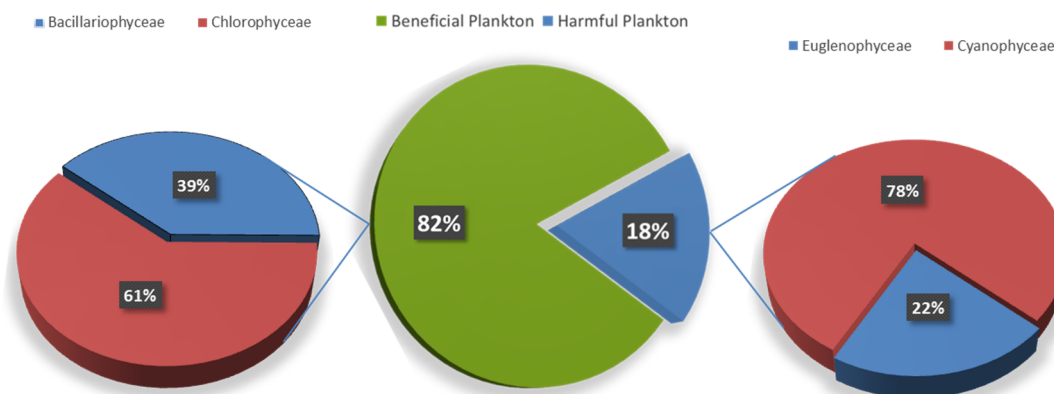


Figure 4. Beneficial and potentially harmful phytoplankton genera composition.

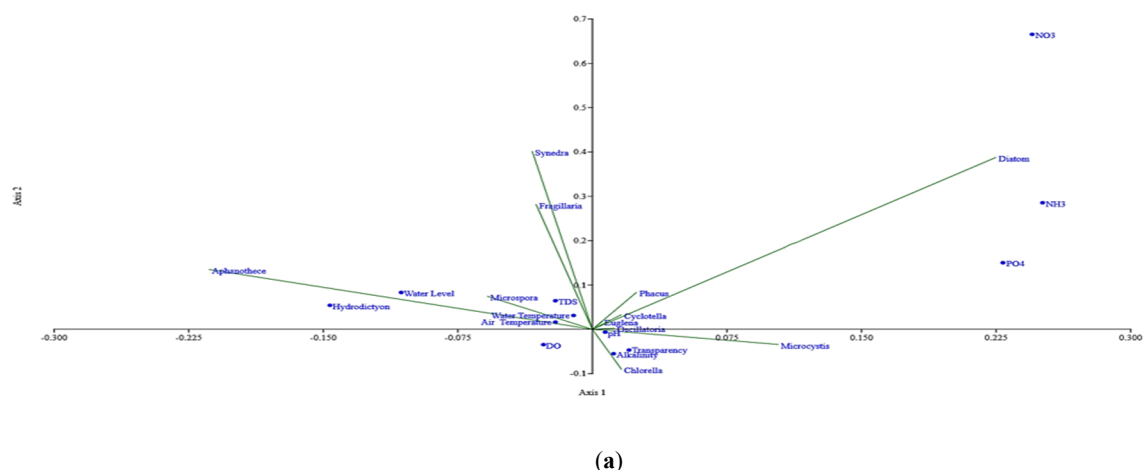
3.5. Relationship between Planktonic Organisms with Physico-Chemical Parameters

The physico-chemical factors affect the distribution of planktonic organisms to different degrees. In the CCA biplot (Figure 5a), while pH and dissolved oxygen have a negative correlation with the distribution of *Hydrodictyon* but water temperature has a positive correlation. *Chlorella* and *Microcystis* have a highly positive correlation with pH and alkalinity. Moreover, the distribution of *Synedra* was found more dependent on TDS. However, in the CCA biplot (Figure 5b), *Phacus* is negatively related to the temperature which indicates the maximum abundance of these at a lower temperature. In addition, the CCA biplot (Figure 5c) shows that the distribution of *Cyclotella* is positively affected by alkalinity. Pearson correlation coefficients were employed to evaluate the interrelationships among physico-chemical variables and their association with plankton community composition across sampling sites (Table 6).

Table 6. Pearson correlation among different physico-chemical parameters and plankton community.

Parameters	Total Phytoplankton	Total Zooplankton	Total Plankton
Water Temperature (°C)	−0.380	−0.225	−0.360
Water level (m)	0.037	0.323	0.083
Transparency (cm)	−0.442 *	−0.569 **	−0.467 *
pH	0.550 **	0.411 *	0.534 **
Dissolved Oxygen (mg/L)	0.433 *	0.395	0.431 *
Total dissolved solids (ppm)	0.205	0.353	0.231
Total alkalinity (mg/L)	0.606 **	0.466 *	0.591 **
Ammonia (mg/L)	0.164	0.091	0.154
Phosphate (mg/L)	−0.411 *	−0.484 *	−0.428 *
Nitrate (mg/L)	0.394	0.333	0.388

* Values indicate a significant difference at 5% significance level based on one-way ANOVA followed by Tukey's test. ** Values indicate a significant difference at 1% significance level based on one-way ANOVA followed by Tukey's test.



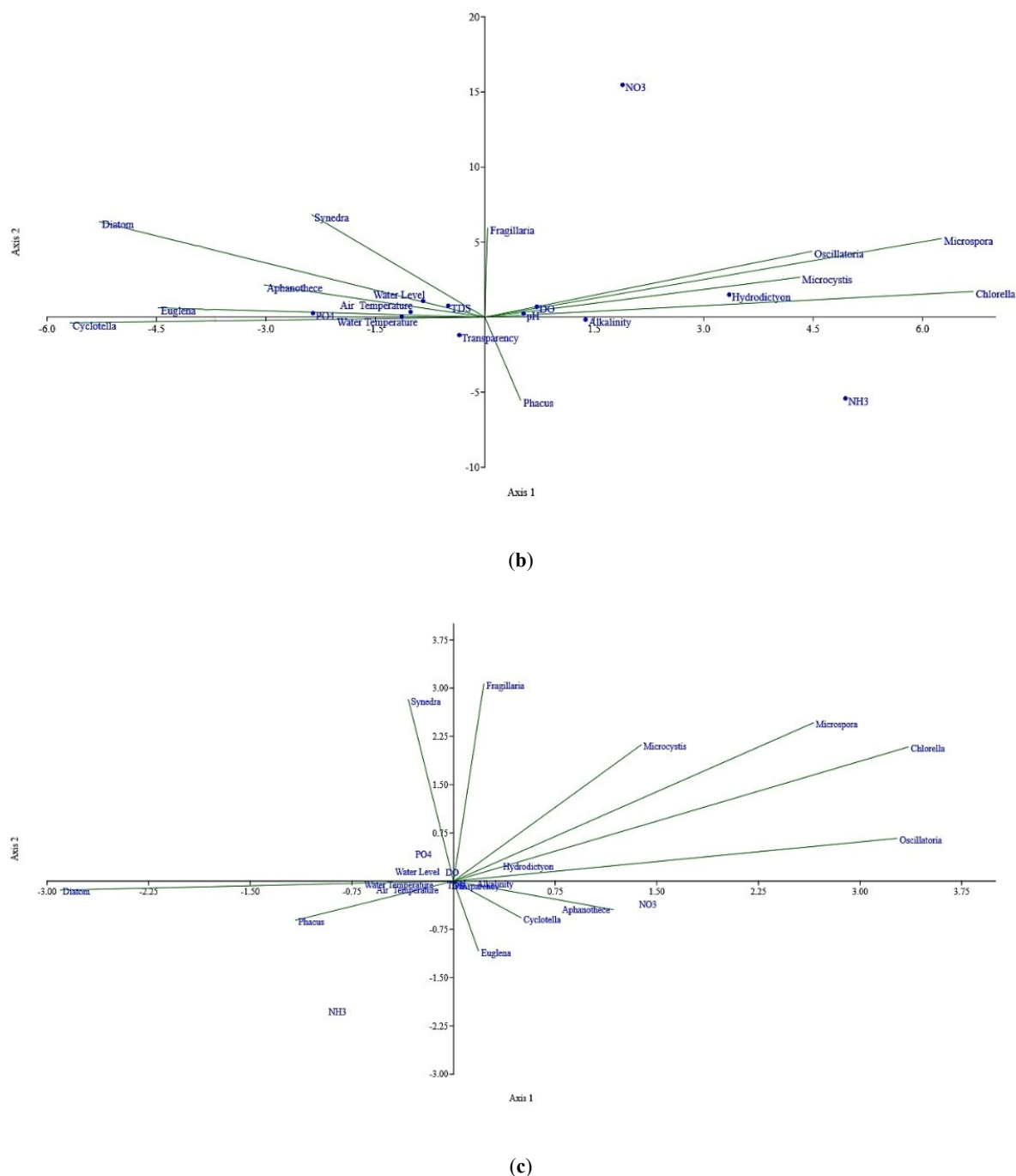


Figure 5. (a) CCA biplot at Treatment I between physico-chemical parameters and planktonic organisms. (b) CCA biplot at Treatment II between physico-chemical parameters and planktonic organisms (c) CCA biplot at control between physico-chemical parameters and planktonic organisms.

3.6. Fish Production in Cage Farm

The initial weight of the fish in both treatments was almost similar (30.7 g). As a result of the greater fish survival rate in Treatment I (71%) compared to Treatment II (66%), Treatment I had the greatest final biomass output, whereas Treatment II had the lowest final biomass production. Furthermore, the final biomass production of *Oreochromis niloticus* found after final harvesting was calculated as 22.9 kg in Treatment I and 21.6 kg in Treatment II, respectively (Table 7).

Table 7. Survival rate and biomass production of *Oreochromis niloticus* at different stocking densities.

Treatments	Stocking Density (No/m ³)	Survival Rate (SR%)	Final Biomass (kg)
Treatment I	25	71	22.9
Treatment II	35	66	21.6

4. Discussion

Different physico-chemical and biological processes in a fish farming operation are influenced by temperature, and the suggested suitable water temperature range for warm-water fish culture varies from 26.06 to 31.97 °C [15]. All of the farmed and control locations had water temperatures that were within acceptable norms, and one of them even matched the value of Ghana's Volta Lake [16,17]. The combination of a warm air temperature, a shallow water depth and an oxygen-rich environment caused the water temperatures of the bodies of water to rise. The observed water level at the study site reported by Islam et al. was 2.64 m [18] and similar observations align with earlier findings that support a healthy environment for fish growth. The suggested suitable transparency range of the freshwater is 35 to 45 cm for the aquatic environment [12]. The recorded transparency of experimental sites was higher than the suitable value due to the addition of the supplementary feeds in the cage area. The average value of transparency was 28.39 cm in the Turag River of Bangladesh due to water pollution [19]. The dissolved oxygen values reflect the biological and physical processes as well as indicate the extent of pollution prevailing in a water body. The ideal level of dissolved oxygen for warm water fish is 6.5 mg/L or above 5 mg/L [20]. Comparisons with dissolved oxygen levels of 7.3–8.1 mg/L found in Lake Volta [15] and Lake Malawi [9] are consistent with the results of the present investigation. Oxygen depletion occurs in water surrounding cages due to uneaten food, respiration of fish and fish waste [4].

The insignificant variation of pH values recorded from the cage farm and control site was within the acceptable range (6.0–9.0) and suitable for fish survival, growth and natural productivity [21]. The pH value of this study is similar to the findings of the Volta Lake in Akosombo which is 7.70 [17]. The fluctuation of pH level occurred because of the absorption and release of CO₂ through photosynthesis and respiration. The total dissolved solid value in the Ramsagar reservoir of Madhya Pradesh in India ranged from 166.37 to 239 mg/L [22]. The maximum total dissolved solid value recorded was 172.66 mg/L during dry season owing to water loss due to concentration of salts in the water and evaporation [23] which is relatively higher than the findings of the study. The optimum nitrate concentration for the fish culture is 0.2 to 10 mg/L [15]. The concentrations of nitrate for both the farmed and control sites ranged between 0.02–0.15 mg/L which is lower than 0.96–0.12 mg/L in the Asukawkaw River [24]. However, nitrate concentrations of 0.29–1.70 mg/L was recorded at Yeji of the Volta Lake in Ghana [16]. The application of fertilizers on farms can lead to excessive deposition of nitrate and phosphate levels in water through leaching and surface runoff. Phosphate is considered as the principal factor produced by the fish farm and it is not harmful at low concentrations but becomes harmful at higher levels [24]. The acceptable value of phosphorus for Nile Tilapia was 0.025 mg/L [25]. The values of phosphate in this study were higher than the range obtained in the Volta Lake [26]. Ammonia is the principal nitrogenous waste through metabolism that is excreted across the gills and feces of fish. The range of ammonia concentration in the cage culture system is from 0.01 to 1.15 mg/L [27] which is consistent with this study's findings. Total alkalinity is used as a tool for the measurement of conditions and productivity of water bodies. The alkalinity ranged from 90 to 160 mg/L and the alkalinity of both farmed and control sites was found similar to Indian reservoirs [28]. The values recorded in farmed sites were higher than the control site and it is comparable to the standard value of alkalinity as >100 ppm [29].

The fundamental information on the dynamic of rapid increase or decrease of plankton population composition, density, and physiological state of organisms is vital to appraise the status of a water body. Although fortnightly sampling was conducted throughout the six-month study period, the present analysis focused primarily on treatment-level comparisons. Long-term monitoring covering multiple seasons is recommended to better characterize seasonal fluctuations in water quality and plankton assemblages. The findings of the study reported that 50 genera of phytoplankton were found in the cage farmed site whereas 31 genera existed in the control site. In the case of zooplankton, the farmed and control sites represent 17 and 13 genera, respectively. The genera that occurred exclusively in cage-farming areas, including *Aphanocapsa* of Cyanophyceae group, *Aulacoseira*, *Amphora*, *Cymbella*, *Gomphonema*, *Nitzschia* and *Pinnularia* of Bacillariophyceae group and *Botryococcus*, *Euastrum*, *Eudorina*, *Mesotaenium*, *Oocystis*, *Pandorina*, *Staurastrum*, *Spirogyra*, *Scenedesmus*, *Stigeoclonium* and *Tetraspora* of Chlorophyceae group. The reason behind the higher number of genera found in the cage farm than the control site is increased nutrient availability associated with cage farming activities [30]. During the

present study, the phytoplankton genus contributed 64% whereas zooplankton occupied 26% of the total plankton genera composition. Among phytoplankton, the most diverse class of phytoplankton found was Chlorophyceae which account for 37% composition, followed by Bacillariophyceae (24%), Cyanophyceae (10%), and Euglenophyceae contributed 3% that is consistent with the findings in Chiffa River, Algeria [31]. The composition and abundance patterns of zooplankton at the studied cage fish farm were comparable to the findings recorded in Lake Victoria [32]. A higher abundance of rotifers and cladocerans were observed next to the cages as an effect of cage farming in the Paranapanema River of Brazil [33] which is similar to the dominance and spatial dispersion of rotifers (12%) and cladocerans (9%) in this study.

Chlorophyceae (50%) and Bacillariophyceae (32%) were marked as beneficial plankton classes that contributed 82% of phytoplankton whereas several Cyanophyceae (14%) and Euglenophyceae (4%) taxa may serve as indicators of nutrient enrichment. However, no evidence of toxin production or harmful algal blooms was evaluated in the present study. Chlorophyceae was found to dominate the beneficial phytoplankton assemblage regarding density and genus number compared to the other plankton classes. In addition, the dominance of Chlorophyceae is favored by a high N:P ratio along with water temperature and pH [34]. Similar results to this study were confirmed and Cyanophyceae's dominance was recorded in eight Kenyan reservoirs due to high nutrient loading in the water column [35]. In addition, Cyanophyceae was noticed as an alarming plankton group that varied significantly and caused pollution of the area where cage farming was accomplished in the river [36]. Several environmental factors for instance low light supply, high pH and high water temperature favored the dominance of Cyanophyceae and Euglenophyceae in the study area [37]. The CCA biplot ordination suggested potential associations between plankton distribution and environmental variables such as temperature, dissolved oxygen, pH, and alkalinity [38]. However, these relationships were interpreted cautiously. It has been observed from the current study that survival rate, growth and production of fish are better in lower stocking density than in higher stocking groups. These findings also demonstrate similar results achieved in a previous study where the best survival and production were attained at lower stocking densities [39]. Within the stocking densities evaluated, the lower stocking density (25 fish m⁻³) resulted in higher survival and final biomass production. These findings suggest that moderate stocking densities may improve production efficiency under the environmental conditions of the Tangon River. The present study focused primarily on water-column characteristics and plankton communities. Important environmental indicators such as sediment quality, benthic macrofaunal assemblages, nutrient accumulation beneath cages and organic matter deposition were not assessed. These variables are frequently used to evaluate long-term ecological impacts of cage aquaculture and should be incorporated into future investigations to provide a more comprehensive assessment of ecosystem responses

5. Conclusions

This study demonstrated that Nile tilapia cage culture in the Tangon River was associated with localized changes in selected water quality and plankton variables. Cage-farming sites supported greater plankton richness and abundance than non-farmed areas, although most differences were not statistically significant. Significant increases were observed for nitrate, ammonia, Cyanophyceae abundance, Copepoda abundance and total zooplankton abundance, indicating moderate nutrient enrichment around cage-farming sites. Therefore, the findings of this study indicate that cage farming was associated with localized changes in selected nutrient and plankton variables rather than broad ecosystem-wide impacts. The lower stocking density (25 fish/m³) produced higher survival and final biomass than the higher density treatment, suggesting improved production efficiency under the environmental conditions of the Tangon River. While the observed changes did not indicate substantial ecosystem degradation during the study period, the results highlight the need for continued monitoring of nutrient dynamics and biological communities. Future studies should incorporate sediment quality, benthic communities, organic matter accumulation, seasonal variations and longer-term assessments to provide a more comprehensive evaluation of the environmental sustainability of river-based cage aquaculture.

Author Contributions

Z.F.: Conceptualization; Z.F. and R.H.: Methodology; Z.F.: Validation; R.H., M.S.A. and M.I.A.L.: Data collection; R.H., M.S.A. and M.M.R.: Investigation, Data curation and analysis; K.M.T.H.: Writing—Original Draft Preparation; Z.F., M.M.R. and K.M.T.H.: Writing—Review and Editing; Z.F.: Supervision, research administration and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding

The authors are thankful to the University Grants Commission (UGC), Bangladesh for giving the funding (No. UGC/5141) necessary to carry out this research.

Institutional Review Board Statement

The animal study was reviewed and approved by the Institute of Research and Training authority, Hajee Mohammad Danesh Science and Technology University (HSTU), Bangladesh. The ethical code is HSTU/IRT/3371, which was approved on 8 November 2021.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data supporting the results of this study can be obtained from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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