

Effects of Cage Aquaculture on Biodiversity of Lake Victoria, Kenya

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How to cite this paper: Orina, T., Kagali, R.N., Mbogo, K., Cooperman, M., Kaufman, L., Okechi, J., Achoki, J., Chepkirui, M., Mwarabu, R.L., Chrispin, N., Morara, G. and Orina, P.S. (2026) Effects of Cage Aquaculture on Biodiversity of Lake Victoria, Kenya. *Open Journal of Ecology*, **16**, 187-201.

<https://doi.org/10.4236/oje.2026.164012>

Received: February 9, 2026

Accepted: April 19, 2026

Published: April 22, 2026

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Abstract

Cage aquaculture is rapidly expanding in Lake Victoria, Kenya, yet its effects on native biodiversity remain poorly understood. This study assessed the impacts of cage aquaculture on wild fish and zooplankton communities by comparing biodiversity indices between experimental cage and control sites between March and August 2024. This study was conducted at the Rasira cages site in Lake Victoria, Kenya. Wild broodstock of *Oreochromis esculentus* were collected from Gesebei, Nyamira County whereas *Oreochromis variabilis* were collected from Oki and Kanyaboli dams in Homa Bay and Siaya County. They were transported to the Kenya Marine and Fisheries Research Institute where they were quarantined for 30 days followed by stocking and pairing in a ratio of 3:1 in 200 m² multiplication pond. After three weeks, fingerlings were collected, stocked in nursery ponds, and fed 45% CP starter feeds until they attained 5 ± 0.01 g where they were conditioned, transported and stocked in the cages at a density of 83 fish/m³. Wild fish were sampled using experimental gill nets, while zooplankton were collected using standard plankton nets to collect data on species biodiversity. Shannon-Wiener diversity indices were calculated for both communities. Results showed that Two-Way ANOVA presented a significant difference between the sampling periods for the two communities ($p < 0.05$). Fish diversity was higher at cage sites ($H' = 1.33 \pm 0.58$) compared to control sites ($H' = 0.99 \pm 0.43$) during March, but this pattern shifted in August with cage sites showing lower diversity ($H' = 0.65 \pm 0.27$)

dominated by haplochromine cichlids (81%). Zooplankton communities were dominated by copepods at both sites, with Cyclopoida comprising 51% - 78% of total density. Species composition shifted between sampling periods, with Thermocyclops showing increased dominance near cages. These findings suggest that cage aquaculture alters local biodiversity patterns, with seasonal variations in fish community structure and potential nutrient enrichment effects on zooplankton. Management strategies should incorporate biodiversity monitoring to ensure sustainable cage aquaculture development in Lake Victoria.

Keywords

Cage Aquaculture, Biodiversity, Lake Victoria, Zooplankton, Haplochromine Cichlids, Shannon-Wiener Index

1. Introduction

Lake Victoria, the largest tropical freshwater lake, once boasted the most diverse fish species including over 350 cichlids providing a rich protein source and economic livelihoods to the riparian communities. The fisheries of Lake Victoria have undergone significant transformation over the past century [1]. Other than the cichlids, the lake supported a diverse ecosystem with numerous indigenous fish species including the nearly extinct tilapiines and cyprinids [2]. However, overfishing, the introduction of invasive species, climate change, and environmental degradation have drastically altered the lake's ecological balance, leading to a decline in native fish populations, including *Oreochromis esculentus* and *Oreochromis variabilis*, and a shift towards dominance by non-native species such as *Nile perch* and Nile tilapia [3]. The introduction of invasive species, notably the *Nile perch*, has had a profound impact on the Lake Victoria ecosystem. While initially boosting commercial fisheries, the *Nile perch's* predatory nature led to the extinction or severe decline of many native fish species. This ecological disruption has had cascading effects on the lake's biodiversity and the livelihoods of communities dependent on its resources [4]. Lake Victoria's commercial fishery has experienced significant changes over the past decades. The most dominant commercial fish species were haplochromines which accounted for 80% of the total catch before the introduction of *Nile perch* [5]. There has been a decrease in catch composition as a result of climate change and overfishing due to increasing demand for food. With a decline in capture fisheries, aquaculture technological advancement including cage fish farming of Nile tilapia was introduced to boost production by enhancing local fish demands and food security [6]. Aquaculture has become increasingly important in Kenya's food system, evolving from a minor role to a mainstream sector. This growth is marked by continued increases in the volume and value chains of freshwater aquaculture, advancements in feed processing, improvements in fish breeding and genetics, particularly for species like Nile tilapia and African catfish [7]. According to the Republic of Kenya, Ministry of Mining,

Blue Economy and Maritime Affairs [8], supported by evolving government policy frameworks and targeted investments. Kenya's aquaculture production has continued its upward trajectory in recent years, with production rising from 27,939 tonnes in 2022 to about 31,767 tonnes in 2023, and further to 33,423 tonnes in 2024 largely driven by cage culture expansion on Lake Victoria, and contributing nearly 20 % of the country's total fish output as capture fisheries stagnate and demand grows.

Lake Victoria faces significant environmental transformation with respect to cage farming [9]. Organic matter, uneaten feeds, and fecal waste increase nutrient loads, turbidity and reduce dissolved oxygen in the water [10]. Further, fish cages can influence fish biodiversity positively by providing refugia and trophic resources. Past studies have documented that well-managed cage farms provide refugia against natural predation and fishing pressure while the increased trophic status can be directly from uneaten feed that dissipates from cages which proliferate from dissolved nutrients [9]. As a result, this will influence the trophic web due to diet shifts towards organic matter [9]. The changes in the foraging behavior of aquatic species are predicted due to energy optimization according to food availability.

Past studies documented that in Lake Victoria, well-managed cage sites act as strategic refuge areas for wild fish against overfishing and predation. Further, the cage structure and nets below the water act as substrate for periphyton and shelter. This potentially aids in restoring and maintaining Lake Victoria's biodiversity and captures fisheries contributing to regional food security. Oketch *et al.*, [9] documented significantly high fish biomass within the cage area in Winam Gulf, Lake Victoria. In Lake Tanganyika and Australia's Murray-Darling Basin, protected areas were found to have higher species' abundances and diversity than unprotected areas [11]. There are limited studies documenting cage aquaculture farms as potential protected areas in Lake Victoria, Kenya.

This study examined the impacts of cage aquaculture on biodiversity and assessed its implications on the conservation and management of Lake Victoria. It was hypothesized that high abundance and diversity of fish species would be found in the cage areas than in the open areas. The results will inform cage farming as a potential refuge in conserving fisheries resources while preserving the ecological integrity of Lake Victoria.

2. Methodology and Methods

2.1. Study Site

This study was conducted at Rio Fish, Rasira cage aquaculture site, located in the Kenyan waters of Lake Victoria (approximately 0° 15'S, 34° 05'E). The Rasira site is situated at the shores of Lake Victoria in Homa Bay County, Kenya. Lake Victoria is the world's largest tropical freshwater lake, with a surface area of approximately 68,800 km² shared among Kenya (6%), Uganda (45%), and Tanzania (49%). The cage farming operation at Rasira comprises multiple floating cages stocked pri-

marily with Nile tilapia (*Oreochromis niloticus*). Control sites were established approximately 500 meters from the cage installations in areas with similar bathymetry and substrate characteristics but no aquaculture activities. The selection of control sites ensured comparable environmental conditions while maintaining sufficient distance to minimize direct influence from cage farming operations.

2.2. Broodstock Collection and Multiplication

Wild mature *O. esculentus* were collected from Gesebei, Nyamira County while *O. variabilis* were collected from both Oki and Kanyaboli dams in Homa Bay, and Siaya Counties. The wild stock was transported in aerated tanks to the Kenya Marine and Fisheries Research Institute (KMFRI), Kegati Aquaculture Research Center. Brooders were quarantined for 30 days and then paired at a 1:3 male to female ratio in 200 m² multiplication ponds, each stocked with 480 fish. *O. niloticus* brooders were sourced from existing F8 generation stock at Kegati and paired similarly. After three weeks, same-age and size fingerlings were collected, stocked in nursery ponds, and fed 45% CP starter feeds until they reached 5 ± 0.01 g. Fingerlings were conditioned in flow-through tanks for three days before transportation to the cages in oxygenated bags. Stocking in cages was done in triplicate at a density of 83 fish/m³ in a 5 by 5 m metallic cage.

2.3. Fish Biodiversity Sampling and Determination

To assess the impact of cage farming on fish biodiversity in Lake Victoria, a multi-phase sampling approach was used between March and August 2024, using monofilament and multifilament gill nets with varying mesh sizes deployed at multiple depths. Fish sampling was conducted between the months of March and August. The study consisted of two distinct phases: 1) baseline sampling conducted prior to the establishment of experimental cages at both farming and control sites to capture pre-existing species composition and abundance; 2) final sampling at six months to assess long-term ecological impacts of experimental cages installed. This phased approach enabled attribution of biodiversity changes to cage farming activities.

Gill nets were strategically placed parallel to the cages to ensure consistent sampling effort on both sides, capturing potential gradients in fish behavior and species composition influenced by cage proximity. Additionally, nets positioned perpendicular to the cages facilitated analysis of fish movement and distribution across zones of influence, revealing the spatial extent of cage-related effects, such as nutrient dispersal. Control nets placed in open waters, distant from cages, provided a reference for natural fish population dynamics, enabling differentiation between farming-induced and natural variations.

Fish specimens were transported to the National Museums of Kenya for identification using taxonomic keys, reference collections, and expert consultation with a museum curator. Voucher specimens were archived in the museum's student collection. This comprehensive methodology, integrating parallel, perpendicular, and control net placements, ensured a robust assessment of cage farming's eco-

logical impact on Lake Victoria's fish biodiversity. Two sets of monofilament gill-nets, one perpendicular and the other parallel to the shoreline, were set at each site at 6:00 a.m. and soaked for 3 hours before retrieval. Mesh sizes of monofilament gillnets are 0.5, 0.75, 1, 1.25, 1.5, and 2 inches. One set of multifilament gillnets 1 inch was set perpendicular to the shoreline soaked for 5 hours for retrievals. Seine net 3 mm mesh size was also used in both around the cages and the control sites. At the cages and control three sets of nets each were used during the sampling event where the nets one parallel and another perpendicular were set to the shoreline.

2.4. Zooplankton Sampling and Analysis

Zooplankton samples were collected between March and August using a 1-meter-long, cone-shaped net with a 60 μm mesh. The net was lowered to near-bottom depths using a graduated rope and vertically hauled, with haul depth recorded. Net contents were washed into 300 ml transparent plastic bottles using a wash bottle, preserved with 5% formaldehyde solution, and transported to the laboratory. In the laboratory, sample volumes were adjusted based on concentration using a graduated beaker. Samples were vigorously stirred for homogeneity, and aliquots were examined in a counting chamber under a binocular dissecting microscope at 40 \times magnification after settling for at least 30 minutes. Small rotifers were further sorted using a fine glass capillary tube, mounted on slides with glycerin-distilled water, and examined under a compound microscope at 100 \times magnification.

Zooplankton were identified to genus or species level using taxonomic keys: Dussart and Defaye (1995) for copepods, Korovchinsky (1992) and Smirnov (1996) for Cladocera, and Koste (1978), Koste and Shiel (1987), and Segers (1995) for rotifers. The volume of lake water filtered (V) was calculated as:

$$V = \text{mouth area of the net } (A) \times \text{depth } (D), \text{ where, } A = \pi r^2$$

The number of zooplankton individuals per litre (Ind/L) is generally calculated by dividing the total number of organisms counted in a sample by the total volume of water filtered (or sampled), adjusted for any dilution or concentration during lab processing. Zooplankton density was calculated using the following formula:

$$\text{Population density (Ind/L)} = \left((N * V_d) / V_f \right) / 1000$$

Where:

N : Number of individuals counted in the aliquot/subsample (mL).

V_d : Volume of the concentrated sample (dilution to the total concentrate volume).

In milliliters (mL).

V_f : Volume of water filtered or sampled in Litres (mL).

$V_f = \text{mouth area of the net } (A) \times \text{depth } (D), \text{ where } A = \pi r^2.$

2.5. Data Analysis

All data collected were keyed in using Ms excel spreadsheet on Windows 2013 and presented as mean \pm standard error. The Fish and zooplankton community structure were assessed using the Shannon-Wiener diversity index (H'), Simpson's di-

versity index ($1/D$), and Pielou's evenness (J).

Differences in diversity indices and species abundance between sampling periods and site types (cage vs. control) were analyzed using two-way analysis of variance (ANOVA), followed by Tukey's Honest Significant Difference (HSD) post hoc tests to evaluate specific differences. Statistical significance was evaluated at $\alpha = 0.05$.

All analyses were performed using the Statistical Package for Social Sciences (SPSS) package (Version 20, SPSS Inc., Chicago, USA) and graphical outputs were generated to illustrate temporal trends and site-specific differences.

The Shannon Diversity Index (H) was calculated as a composite measure of species diversity for each site and station, following Shannon and Weaver (1963) where H value gives an indicator of overall diversity. It was supplemented with two other parameters: the simple number of species present (S), and "evenness" of the community (J) following Pielou (1969). Species evenness (J) ranges from zero to one, with zero signifying low diversity (no evenness) and one, indicating high diversity (complete evenness).

(a) Shannon-Wiener Index (H')

$$H' = -\sum_{i=1}^S p_i \ln p_i$$

Where:

- $p_i = \frac{n_i}{N}$
- n_i = number of individuals of species i .
- N = total individuals in the sample.
- S = species richness.

(b) Species Richness (S)

Total number of species recorded per net set.

(c) Pielou's Evenness (J')

$$J' = \frac{H'}{\ln S}$$

(d) Simpson's Diversity (if used)

Specify whether:

$$D = \sum p_i^2$$

or

$$1 - D$$

or

$$1/D$$

3. Results

Fish community composed of three different categories: *Haplochromis* spp, *Lates niloticus* and *R. argentea*. In March, *R. argentea* recorded high abundance before setting up the experimental cages, followed by *Haplochromis* spp and *Lates niloticus*. In August, all the three species recorded an increase in numbers with *Haplo-*

chromis spp recording the highest as shown in **Table 1** and **Table 2**. The Fish community structure differed significantly between sampling periods. Shannon diversity was higher in March 2024 ($H' = 0.738 \pm 0.152$) compared to August 2024 ($H' = 0.629 \pm 0.143$), indicating a decline in species evenness over time (Tukey HSD, $p < 0.05$).

During March, *Rastrineobola argentea* was the dominant species, while *haplochromine* cichlids and *Lates niloticus* contributed smaller proportions to the total catch (**Figure 1**). In contrast, August sampling revealed a pronounced shift toward haplochromine dominance, which accounted for 81% of total fish abundance, representing a statistically significant increase relative to March (Tukey HSD, $p < 0.05$).

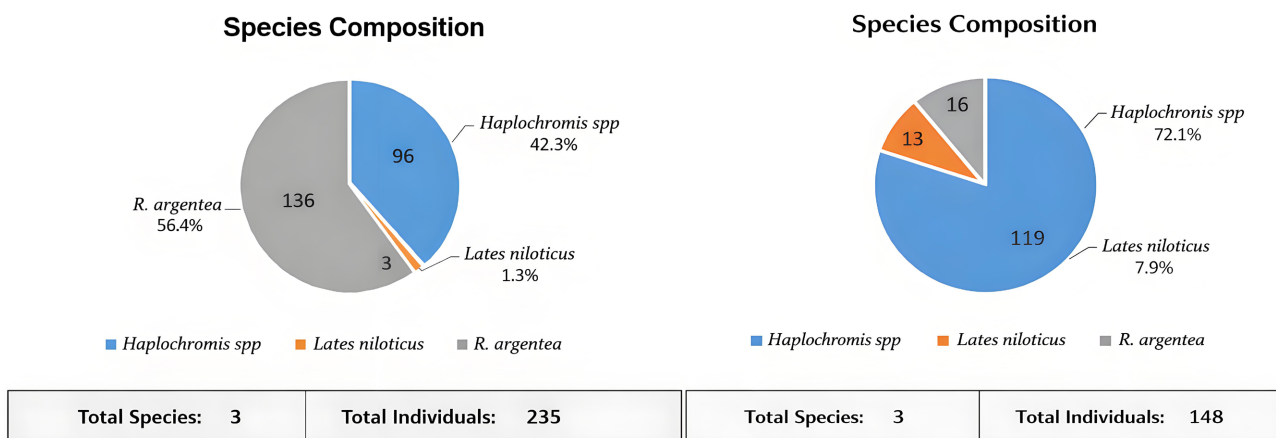


Figure 1. Fish community composition at Rasira cage aquaculture site during March and August 2025. Pie charts show the relative abundance (%) of fish species collected using experimental gill nets. March sampling (left) shows a more even distribution with *Rastrineobola argentea* as the dominant species, while August sampling (right) reveals a marked shift toward Haplochromines dominance (81% of total catch).

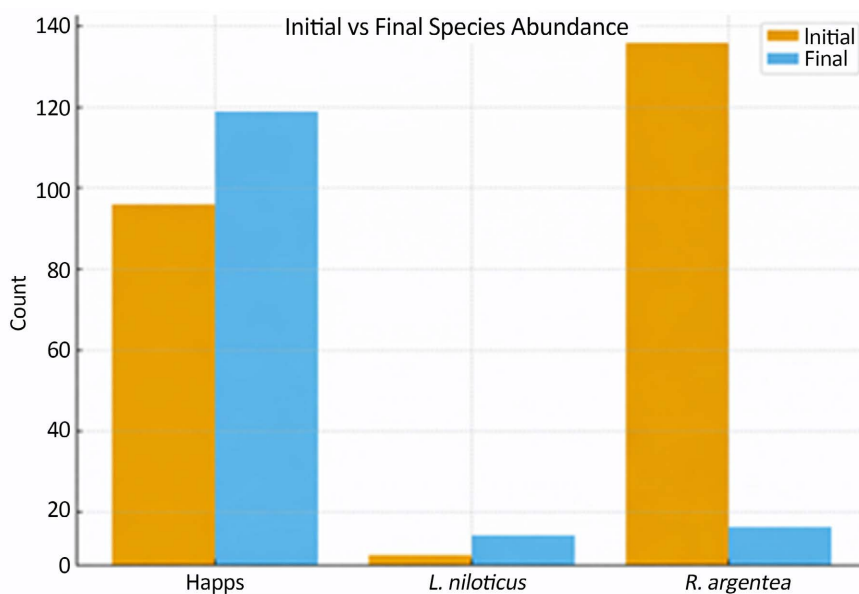


Figure 2. Comparison of initial and final species abundance showing changes in population counts of *Haplochromis* spp. (Haps), *Lates niloticus*, and *Rastrineobola argentea* over the study period.

By August, species diversity had declined markedly, with haplochromines becoming overwhelmingly dominant, accounting for 81% of the total fish population. Comparison of initial and final species abundance revealed contrasting trends among dominant taxa (Figure 2): haplochromine abundance increased significantly over the study period ($p < 0.05$), while *R. argentea* showed a marked decline ($p < 0.05$), and changes in *Lates niloticus* abundance were not statistically significant ($p > 0.05$). This shift in species composition suggests that cage aquaculture may be altering the surrounding environment, potentially favoring opportunistic haplochromine cichlids. The reduced presence of *R. argentea* and *L. niloticus* in August may reflect changes in food availability, habitat structure, or competitive interactions near the cages, and the observed decline in biodiversity could have long-term consequences for the ecological balance of the lake (Figure 3).

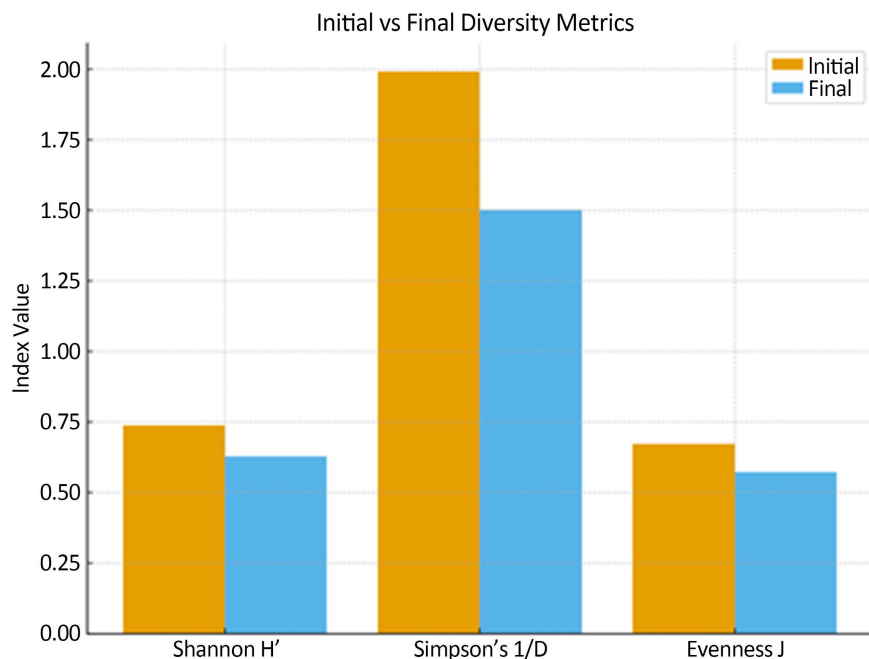


Figure 3. Comparison of initial and final community diversity metrics, including Shannon-Wiener diversity index (H'), Simpson's diversity index ($1/D$), and Pielou's evenness (J).

The change in biodiversity, as reflected by the decreasing Shannon Index, suggests that cage aquaculture may be impacting the balance of fish species in the lake, favoring species like *Haplochromines*, possibly due to alterations in food availability or habitat conditions around the cages. This trend could have long-term implications for the ecological health of the lake.

Zooplankton samples were collected at Rasira Fish Cages using a 30 cm diameter plankton net through three vertical hauls from 12 m depth. Filtered volume was calculated as $V_f = A \times D \times H$, where A is the net mouth area (0.07065 m^2), D is haul depth (12 m), and H is the number of hauls (3), giving a total filtered volume of 2.5434 m^3 (2543.4 L). Samples were concentrated to 600 mL. Three 1 mL

subsamples were enumerated under a microscope, and mean counts were scaled to the total sample volume. Zooplankton abundance was expressed as individuals per liter (Ind/L) by dividing the estimated total individuals by the filtered water volume in liters.

Total zooplankton abundance increased modestly between March and July at both cage and control sites. Mean abundance increased by approximately 7% at cage sites and 6% at control sites, although differences between site types were not statistically significant ($p > 0.05$). A pattern that may align with increased nutrients from rainfall runoff in tropical lakes. Copepods increased in both (cages: +5.5%; controls: +7.9%), maintaining dominance, while *cladocerans* showed minor fluctuations (cages: -3%; controls: +6%). Community composition, however, differed significantly. Rotifer abundance increased significantly within cage sites ($p < 0.05$), driven primarily by increases in *Brachionus calyciflorus*, *B. falcatus*, and *Keratella tropica*. In contrast, rotifer abundance declined in control sites, possibly indicating aquaculture-driven eutrophication favoring rotifer proliferation near cages. These shifts suggest environmental influences; though natural variability cannot be ruled out.

Copepods remained the dominant group across all sites and sampling periods, with cyclopoids and nauplii showing moderate but significant increases over time ($p < 0.05$). Several cladoceran taxa, including *Daphnia lumholtzi*, declined significantly in cage sites ($p < 0.05$), while *Ceriodaphnia cornuta* emerged only in control sites. Notably, *Trichocerca* sp. disappeared from cages (0.59 to 0 Ind/l), while *Ceriodaphnia cornuta* emerged in controls (0 to 1.57 Ind/l), highlighting potential species-specific responses to habitat conditions.

The zooplankton data from Rasira fish cages and control sites in Lake Victoria, Kenya, provides a snapshot of community dynamics over a one-month interval in 2024, revealing subtle yet noteworthy shifts that may inform broader ecological patterns in tropical aquaculture settings. Lake Victoria, Africa's largest freshwater lake, supports extensive tilapia cage farming, with Rasira representing a key site where such activities intersect with natural plankton communities. The dataset encompasses densities (Ind/l) and percentages for 13 taxa across three main groups: copepods (*Copepod nauplius* larvae, *Cyclopoida*, *Calanoida*), cladocerans (*Diaphanosoma excisum*, *Moina micrura*, *Daphnia lumholtzi*, *Ceriodaphnia cornuta*, *Bosmina longirostris*), and rotifers (*Brachionus calyciflorus*, *Brachionus falcatus*, *Keratella tropica*, *Asplanchna* sp, *Trichocerca* sp). These taxa are emblematic of African lake zooplankton, where cyclopoids often predominate due to their adaptability in nutrient-rich waters.

Sampling depths varied (6.1 - 14.2 m), with volumes filtered (1229 - 3009 L) and subsampling yielding average counts converted to Ind/l. March 18, 2024, data reflect late dry season conditions, while April 16 captures the early long rains, a period when runoff may elevate nutrients and plankton growth in tropical systems, though fluctuations are typically less extreme than in temperate zones. Overall abundance increased, consistent with seasonal peaks observed in similar habitats, potentially amplified by aquaculture waste in cages.

Table 1. Species diversity per sampling site.

Date	Site Type	Total Abundance (Ind/l)	Species Richness	Shannon Index	Copepoda %	Cladocera %	Rotifera %
2024-03-18	Cages	401.09	13	2.08	87.85	7.43	4.71
2024-03-18	Controls	803.43	12	2.42	89.46	5.77	4.77
2024-07-16	Cages	429.81	12	2.14	86.53	6.73	6.78
2024-07-16	Controls	854.16	13	2.36	90.80	5.78	3.42

Table 1 summarizes key indicators. Abundance per site type rose modestly, with controls consistently higher, possibly due to less disturbance or greater spatial coverage (three vs. two stations). Shannon indices, measuring evenness and richness, hovered in the moderate range (2.0 - 2.5), typical for eutrophic tropical lakes where dominant taxa like copepods suppress diversity. The slight cage increase (2.08 to 2.14) may indicate improved evenness from rotifer gains, while the control decrease (2.42 to 2.36) could reflect copepod intensification. Richness shifts highlight vulnerability: cages lost *Trichocerca* sp., a rotifer sensitive to eutrophication, while controls gained *Ceriodaphnia cornuta*, a cladoceran that thrives in varied conditions.

Table 2. Species composition in the selected sampling sites and periods.

Taxa	March Cages (Ind/l)	Agust Cages (Ind/l)	% Change Cages	March Controls (Ind/l)	April Controls (Ind/l)	% Change Controls
<i>Copepod nauplius larvae</i>	135.52	148.4	9.5	346.48	373.92	7.9
<i>Cyclopoida</i>	191.56	192.98	0.7	329.34	356.64	8.3
<i>Calanoida</i>	25.31	30.38	20	42.88	45.03	5
<i>Diaphanosoma excisum</i>	14.01	15.64	11.6	21.46	27.11	26.4
<i>Moina micrura</i>	2.81	3.66	30.2	9	8.26	-8.2
<i>Daphnia lumholzti</i>	2.99	1.42	-52.5	4.04	2.11	-47.8
<i>Ceriodaphnia cornuta</i>	0.71	2.42	240.8	0	1.57	+∞ (new)
<i>Bosmina longirostris</i>	9.27	5.77	-37.8	11.89	10.3	-13.4
<i>Brachionus calyciflorus</i>	3.66	7.45	103.6	2.89	2.43	-15.9
<i>Brachionus falcatus</i>	2.27	5.49	141.9	3.12	2.83	-9.3
<i>Keratella tropica</i>	7.45	11.39	52.9	11.68	13.78	17.9
<i>Asplanchna</i> sp	4.94	4.81	-2.6	17.89	7.93	-55.7
<i>Trichocerca</i> sp	0.59	0	-100	2.77	2.24	-19.1

Copepods drove overall increases, with *nauplii* and *calanoids* showing consistent gains, potentially benefiting from seasonal nutrient influxes. Cladocerans like *Daphnia lumholzti* declined sharply, a trend that might signal sensitivity to warming or competition in enriched waters. Rotifers displayed site-specific responses: surges in *Brachionus* spp. and *Keratella* in cages suggest eutrophication favoring these opportunistic groups, while *Asplanchna* declines in controls could

indicate reduced predation or habitat changes. These patterns echo literature on cage farming, where excess feed and waste elevate phosphorus and nitrogen, boosting abundance but altering composition toward smaller, less diverse assemblages.

In cages, the rotifer uptick (from 18.90 to 29.14 Ind/l) aligns with studies showing nutrient enrichment from aquaculture promoting rotifer dominance, potentially at the expense of larger crustaceans. The loss of *Trichocerca sp.* may reflect competitive exclusion or sensitivity to turbidity from cage operations. Controls, conversely, exhibited more balanced gains, with *Ceriodaphnia*'s emergence possibly tied to natural recovery or lower disturbance, underscoring controls' role as baselines. Biodiversity implications include potential functional losses: reduced richness in cages could impair food web resilience, as zooplankton underpin fish production, while controls' rotifer decline might affect nutrient cycling. Seasonal context is key March-August transitions in Lake Victoria often see rising abundances with rains, but aquaculture may exacerbate shifts toward eutrophication-tolerant taxa. Long-term, such dynamics warrant sustainable practices, like optimized feeding, to mitigate diversity erosion observed in global fish farming studies.

4. Discussion

Cage aquaculture in Lake Victoria according to the study demonstrates an association between its existence with measurable but complex alterations in both fish and zooplankton community structure. Further, it depicts implications for biodiversity conservation and ecosystem functioning. While overall changes were moderate over the study period, evident directional shifts in species diversity indices, dominance, and functional groups suggest early ecological responses to cage farming activities anchored on strong seasonal dynamics synonymous with tropical lakes. The observed decline in fish biodiversity from March of the study period indicates a reduction in species evenness and increasing dominance by Haplochromines around the cage sites. In the same month, the relatively higher Shannon index reflected a more balanced assemblage, with *R. argentea* dominating but still coexisting with the Haplochromines and *L. niloticus*. Four months later in August, a major upward shift by Haplochromines resulted in their accounting for over 80% of the catch, signaling a shift toward opportunistic resilient taxa. Such dominance shifts are consistent with past studies in L. Victoria and other tropical aquatic systems, where nutrient enrichment and habitat modification may potentially benefit small-bodied, fast-reproducing species capable of exploiting localized productivity rise around cages [12] [13]. Furthermore, the submerged cage structure and nets provide substrate for the establishment of periphyton providing microhabitat and foraging ground. Decline of *R. argentea* and *L. niloticus* may reflect changes in primary productivity, prey availability, altered habitat use, or competitive displacement, rather than direct exclusion. Importantly, the magnitude of diversity loss observed here is modest, suggesting that cage aquaculture

acts as a localized ecological filter rather than a lake-wide driver of biodiversity collapse, at least in the short term. However, no introduced or wild tilapiines were recorded during the study.

Meanwhile, total zooplankton abundance increased slightly in both cage and control sites, reflecting seasonal nutrient enrichment associated with the onset of long rains. However, compositional changes differed between site types. The pronounced increase in rotifers within cages, particularly *Brachionus* spp. and *Keratella tropica*, contrasts with declines or modest increases in controls, indicating localized eutrophication effects linked to cage operations. It is important to note that Rotifers are widely recognized as indicators of nutrient enrichment and organic loading [14] [15], and therefore their proliferation near cages suggests that uneaten feed and metabolic waste likely enhanced microbial and phytoplankton production, creating favorable conditions for small, opportunistic grazers. On the other hand, the decline of sensitive taxa such as *Trichocerca* sp. and the reduction of large-bodied Cladocerans (*Daphnia lumholtzi*) within cages point to reduced habitat suitability for taxa less tolerant to increased turbidity, organic enrichment, or altered predator regimes. However, the study findings based on Shannon diversity indices for zooplankton which remained within a moderate range, underscores the buffering capacity of Lake Victoria's large, eutrophic system. Controls maintained higher diversity and stability, reinforcing their role as ecological baselines and highlighting the importance of spatial zoning in cage aquaculture planning.

A critical insight from this study is the interaction between seasonal ecological alterations and aquaculture impacts. In tropical lakes such as Lake Victoria, rainfall-driven nutrient inflows strongly influence plankton dynamics, often undermining the recognition of anthropogenic indicators. However, the disproportionate rise in rotifers and selective loss of sensitive taxa near cages suggests that aquaculture intensifies eutrophication signals beyond natural seasonal variability. This finding aligns with regional studies showing that while Lake Victoria can dilute and assimilate moderate nutrient inputs, localized ecological effects accumulate with increasing cage density and poor feed management [13] [16]. Thus, although short-term impacts appear minimal, intensified cage farming especially around unsuitable areas could progressively erode biodiversity and alter trophic pathways. The combined fish and zooplankton responses observed here indicate a shift toward simplified food webs dominated by opportunistic species, a pattern commonly associated with eutrophication and habitat homogenization. Such changes may have cascading effects on fish recruitment, energy transfer efficiency, and ecosystem resilience. While increased plankton productivity may temporarily benefit certain fish species, long-term biodiversity loss could undermine ecosystem stability and artisanal fisheries that depend on diverse fish assemblages. Importantly, the study supports the view that cage aquaculture is not inherently incompatible with biodiversity conservation, provided it is managed within ecological thresholds. Optimized feeding regimes, site rotation, biomass limits, and con-

tinuous ecological monitoring can significantly reduce negative impacts while sustaining production benefits.

5. Conclusions

This study provides empirical evidence that cage aquaculture in Lake Victoria induces localized, measurable changes in fish and zooplankton biodiversity, characterized by declining fish evenness, increased dominance of opportunistic species, and shifts in plankton composition toward eutrophication-tolerant taxa. While overall impacts during the study period were moderate and strongly mediated by seasonal dynamics, the observed trends signal early ecological responses that could intensify with prolonged or commercialized intensive cage aquaculture.

These study findings highlight the importance of adaptive, ecosystem-based management of cage aquaculture, including spatial zoning, nutrient load control, and long-term biodiversity monitoring. Maintaining control areas and integrating plankton indicators as well as other innovative systems into routine assessments will be critical for detecting early warning signs of ecosystem stress. Ultimately, sustainable cage aquaculture in Lake Victoria must balance food security and economic gains with the preservation of ecological integrity, ensuring that productivity enhancements do not come at the expense of biodiversity and long-term ecosystem resilience.

Acknowledgements

I am deeply grateful to PlusFish Philanthropy for their generous support on this project. Their commitment to promoting research and engagement in the protection of aquatic ecosystems and the vital benefits they provide has been instrumental in enabling the completion of this work. Without their funding and encouragement, this manuscript would not have been possible.

Special thanks to the founder and team at PlusFish Philanthropy for their dedication to conserving freshwater biodiversity and supporting initiatives that advance scientific understanding and conservation efforts worldwide.

Conflicts of Interest

The authors declare no conflicts of interest.

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