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Research Article

In situ Captive Growth Performance and Conservation Potential of Native Tilapiines in Lake Victoria, Kenya: A Case Study of Rasira Beach

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Abstract

The endangered native tilapiine cichlids *Oreochromis variabilis* and *Oreochromis esculentus* have declined dramatically in Lake Victoria due to introduced species, overfishing, and habitat degradation. This study evaluated the potential of cage aquaculture as an *ex-situ* conservation tool for these species by assessing growth performance, survival, natural reproduction, and water quality impacts under controlled cage conditions in Lake Victoria, Kenya. A six-month completely randomized experiment was conducted using 8 m^3 cages stocked with 30 fish m^{-3} (initial weight 5 ± 0.01 g) at Rio Fish Farm, Homa Bay County. *Oreochromis niloticus* served as a comparative reference. Growth performance differed significantly among species (two-way ANOVA, species effect: $F_{(2, 24)} = 124.7$, $p < 0.001$). *O. niloticus* attained the highest final weight (185.39 ± 0.93 g), whereas *O. variabilis* (47.26 ± 5.25 g) and *O. esculentus* (46.03 ± 1.99 g) grew more slowly (Tukey's HSD, $p < 0.001$ for both comparisons). Feed conversion ratios (FCR) were significantly lower for *O. niloticus* (1.77) compared to *O. variabilis* (5.26) and *O. esculentus* (5.48) (Tukey's HSD, $p < 0.001$). Survival rates were high across all species: *O. niloticus* (88.55%), *O. esculentus* (85.55%), and *O. variabilis* (75.9%), with significantly lower survival in *O. variabilis* compared to *O. niloticus* (Tukey's HSD, $p = 0.018$). Critically, fry of both native species were observed throughout the trial, indicating successful natural spawning under cage conditions, a key finding for conservation breeding. Water quality monitoring revealed significantly elevated total nitrogen (up to 463.5 ± 54.7 μg L^{-1}; $p = 0.008$) and total phosphorus (up to 41.5 ± 2.2 μg L^{-1}; $p = 0.042$) at cage sites compared to open water controls. We conclude that cage aquaculture offers a viable pathway for *ex-situ* conservation of *O. variabilis* and *O. esculentus*, particularly through captive breeding and stock enhancement. However, species-specific feed development and strict nutrient management are required to overcome current growth limitations and mitigate eutrophication risks. Levels of heavy metals (Fe, Zn, Cu, Pb, Ni, and Cd) in five commercial fish species collected from the Red Sea and Gulf of Aden, mainly *Pomadasys argenteus, Aprion virescens, Valamugil sehli, Epinephelus areolatus* and *Thunnus tonggol* were measured to assess contamination and health risks. The flame Atomic Absorption Spectrophotometry (AAS) method was adopted for measuring all selected elements. The results showed that variations in heavy metal concentrations within the muscle tissues of the examined fish were mainly attributed to the geochemical nature of beach deposits rather than anthropogenic input. All muscle samples analyzed had concentrations of Fe, Ni, Zn, Cu, Pb, and Cd below the standards reported by the National Health and Medical Research Council (NHMRC). Thus it was concluded that the investigated heavy metals do not present an environmental hazard for the present time. Cd, Ni, and Pb are harmful and cause cancer diseases.

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Introduction

Globally, freshwater ecosystems face unprecedented threats from a combination of climate change, overexploitation, pollution, habitat degradation, and the introduction of invasive species [1]. These stressors are compounded by rapid population growth and rising demands for protein-rich foods such as fish. The world's human population is projected to grow from 8.1 billion to approximately 9.7 billion by 2050 [2], posing significant challenges to achieving food security and the United Nations Sustainable Development Goals (SDGs), particularly SDG 2, which focuses on ending hunger and promoting sustainable agriculture. Although significant efforts have been made to address global food insecurity, the availability of affordable and sustainable protein sources remains inadequate, particularly in developing regions. In this context, aquatic foods, especially fish, have been recognized as a critical component of global food and nutrition security due to their affordability, nutritional benefits, and wide availability [2].

Despite the recognized importance of fish as a protein source, marine and freshwater wild fish stocks are under immense pressure globally, with declining catches reported across numerous regions, including Africa. Freshwater ecosystems, though accounting for only about 1% of the Earth's surface, host approximately one-third of all vertebrate species and nearly half of the world's fish species [3]. These ecosystems are among the most threatened globally, facing persistent and emerging threats such as pollution, habitat alteration, climate change, and invasive species introductions [4]. In Africa, Lake Victoria, the world's second-largest freshwater lake and the largest in the tropics, exemplifies these challenges. The lake's fisheries, once dominated by native tilapiine species, have been significantly altered by the introduction of non-native species such as Nile perch (*Lates niloticus*) and Nile tilapia (*Oreochromis niloticus*), leading to drastic declines in native fish populations [5,6].

Of particular concern is the decline of indigenous tilapiine cichlids, *specifically Oreochromis variabilis* and *Oreochromis esculentus*, which historically contributed significantly to the lake's fisheries and local diets. These species, once common in commercial catches, are now rarely encountered and are listed as endangered by the IUCN [7] due to factors such as competition from introduced species, habitat degradation, overfishing, and hybridization. The disappearance of these native species not only signifies a loss of biodiversity but also deprives local communities of culturally and nutritionally significant resources. Indigenous tilapiines are known for their nutritional value, providing high-quality proteins and essential fatty acids, particularly omega-3 and omega-6 polyunsaturated fatty acids (PUFAs), which play crucial roles in human health by supporting immune function, reducing disease susceptibility, and contributing to hormonal regulation [8,9]. However, the supply of these beneficial nutrients from wild fisheries is declining, exacerbating nutritional deficiencies in vulnerable populations.

Aquaculture has emerged as a sustainable solution to address declining wild fish stocks and the increasing demand for fish protein. Cage aquaculture, in particular, has gained prominence globally due to its efficient use of space and potential to produce high yields within freshwater bodies such as lakes and reservoirs. In Kenya, cage fish farming is expanding rapidly, with Lake Victoria hosting the largest cage aquaculture operations, producing an estimated 50 tonnes of fish per day. This method aligns with Kenya's Blue Economy strategy, aimed at promoting sustainable exploitation of aquatic resources to enhance food security, create employment, and support economic growth [5,10].

Despite its benefits, cage aquaculture also poses potential ecological risks, including localized nutrient enrichment from uneaten feed and fish waste, habitat alteration, the introduction of non-native species, genetic dilution of wild stocks through escapes and hybridization, and the spread of diseases. These risks are particularly pertinent in ecologically sensitive and already stressed ecosystems like Lake Victoria [11]. However, if properly managed, cage aquaculture could contribute positively to conservation efforts by serving as a refuge for endangered species, providing breeding grounds protected from overfishing, and acting as aggregation points for fish populations [12].

In light of these opportunities and challenges, this study seeks to evaluate the potential of cage aquaculture systems to support the conservation of endangered native tilapiine cichlids, specifically *O. variabilis* and *O. esculentus*, in Lake Victoria. By assessing their growth performance, survival, and reproductive capacity under controlled cage culture conditions, this research aims to explore the viability of using these species in aquaculture as part of a broader conservation strategy. Additionally, the study examines the impacts of cage aquaculture on in-situ water quality, providing critical insights into the environmental sustainability of this farming method within Lake Victoria's unique ecosystem.

It was hypothesized that culturing the endangered species within cage systems could offer conservation benefits by reducing pressure on wild populations, enhancing their survival and reproductive output under controlled management, and contributing to biodiversity restoration initiatives. Furthermore, the study anticipated that cage aquaculture, if not properly managed, could lead to localized changes in water quality due to nutrient loading.

Materials and methods

Ethical approval

Ethical approval for this study was obtained from the Kenya Marine and Fisheries Research Institute (KMFRI). All experimental procedures involving fish handling, transportation, breeding, and sampling were conducted in accordance with KMFRI guidelines for the care and use of aquatic organisms in research.

Study period and area

The study was conducted at Rio Fish Farm, located on the shores of Lake Victoria in Homa Bay County, the southwestern

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part of Kenya. It lies at latitudes 0°45S, 34°04'E, at an elevation of 1147.66 meters above sea level, with an average annual temperature range of 30 °C to 35 °C and an average annual rainfall of 684 mm. The main activity around this region is fishing supplemented with subsistence farming of crops grown mostly under irrigation, which include watermelons, tomatoes, mangoes, onions, finger millets, maize, sorghum, and kales among others. Animals reared include cattle, goats, and sheep, and a few people also engage in cage fish farming of tilapia. The study site was selected due to its climatic conditions, availability of space to support the research, and the Boston Project requirement for research in Lake Victoria basin regions. Water samples were transported to JKUAT Environmental Engineering Lab for analysis.

Broodstock collection and multiplication

Wild mature *Oreochromis esculentus* and *Oreochromis variabilis* were collected from selected colonial and non-colonial dams within Nyamira County, Homa Bay County, and Siaya County along the Kenyan side of Lake Victoria. Prior to transportation, broodstock were identified and screened to species level based on morphological characteristics using standard taxonomic features, including body coloration, gill raker patterns, body depth, head profile, scale counts, and fin morphology, to ensure species purity and exclude putative hybrids. Although molecular genetic analysis was beyond the scope of the present study, strict morphological screening based on established taxonomic descriptors was employed to minimize the inclusion of putative hybrids and maintain broodstock integrity. The broodstock were then transported to the Kenya Marine and Fisheries Research Institute, Kegati Aquaculture Research Center in Kisii County. A total of 600 *O. esculentus* and 575 *O. variabilis* were collected and transported in 500 L circular tanks using a DC-powered aeration system to maintain dissolved oxygen levels between 5–6 mg L^{-1}. Upon arrival, broodstock were quarantined in separate ponds by species for 30 days. Broodstock collection from multiple locations was undertaken to capture representative genetic diversity of remnant native populations and to avoid reliance on a single, potentially bottlenecked population. During multiplication, brooders were screened to exclude individuals with deformities, disease, or ambiguous morphological characteristics suggestive of hybridization, and pairing was conducted at a ratio of 1:3 (male:female) in 200 m^2 ponds, with each pond stocked with 480 fish. *Oreochromis niloticus* broodstock were obtained from existing stocks at KMFRI Kegati and subjected to similar breeding conditions to ensure uniformity in age for subsequent growth trials. Fish were fed thrice daily using 3 mm commercial pellets containing 30% crude protein (CP). After three weeks, fry of uniform size were harvested, transferred to nursery ponds, and fed 45% CP starter diets to satiation until reaching an average weight of 5 ± 0.01 g. Before transportation, fingerlings were conditioned in 3 m^3 flow-through tanks for 3 days. A total of 2,200 mixed-sex fingerlings per species were packed into four oxygenated bags containing 550 fish per bag, including a precautionary 10% allowance for transport-related mortality. Transportation from KMFRI Kegati to the cage site at Rasira in Homa Bay County was conducted between 0400 h and 0700 h to minimize thermal stress.

Experimental design and cage setup

The experiment employed a completely randomized design consisting of three treatments representing the three tilapia species, each replicated three times. Fingerlings with an initial average weight of 5 ± 0.01 g were stocked at a density of 30 fish m^{-3}. Each species treatment consisted of three independent cage replicates, and each cage represented an experimental unit during statistical analysis. Mixed-sex populations were intentionally used to evaluate the natural reproductive potential of the endangered native species under cage conditions, which was central to assessing their conservation applicability. Nine floating cages measuring 2 m × 2 m × 2 m (8 m^3) were fabricated using galvanized metallic frames and installed at Rasira Beach within the Rio Fish Farm aquaculture zone. Each cage was fitted with an internal hapa and an external double-layer predator exclusion net of 1-inch mesh size. The cages were positioned at sufficient distance from commercial production cages to minimize external operational influences.

Feed and feeding management

Fish were fed using commercially available floating tilapia feeds commonly utilized by cage fish farmers in Kenya to evaluate the practical aquaculture viability of the indigenous species under prevailing commercial production conditions. During the first two months of culture, fingerlings were provided with starter diets containing 40% crude protein (CP) to support early growth and adaptation to cage conditions. The protein level was subsequently reduced to 35% CP during the third and fourth months using grower pellets, and further reduced to 30% CP during the final two months using finisher diets to reflect standard commercial feeding practices adopted in tilapia cage aquaculture. The progressive reduction in dietary protein levels was intended to simulate realistic production systems while assessing the growth response, feed utilization efficiency, and production potential of *Oreochromis esculentus* and *Oreochromis variabilis* relative to *Oreochromis niloticus* under commercially relevant culture conditions. Feeds were manually broadcast into the cages through the upper openings of the hapa. The daily feed ration was divided into two equal portions and administered between 0900–1000 h and 1500–1600 h. Feeding rates were adjusted fortnightly based on biomass estimates and growth stage, which were determined through random sampling of 30 fish per cage. During each sampling event, cages and net structures were simultaneously inspected for physical damage, fouling, or net tears to ensure optimal rearing conditions and prevent fish escape.

Fish sampling and growth parameter determination

To assess growth and survival, sampling was performed monthly to minimize stress, while mortality was recorded daily to monitor survival. Access to cages was achieved using a motorized boat. Aboard were 20-liter capacity buckets, which were half-filled with lake water for sample transportation to the lake shore for length and weight measurements. Length and weight parameters were measured using a measuring board (100 cm ruled) and a sensitive weighing balance (WTC 2000®) with two-decimal-place readability. A 2-meter-long scoop net

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with a mesh size of 0.5 mm was used to transfer fish from the cages to the buckets. Once measurements and biometric data were recorded, the fish were placed in a holding container with aerators until all fish had been sampled. Afterward, they were returned to their respective rearing units.

Growth performance calculations

- Monthly growth (MG) (g) = Final weight / Time (months)
- Body weight gain (BWG) (g) = Final weight – Initial weight
- Specific growth rate (SGR) (% day^{-1}) = 100 × [(ln Final weight – ln Initial weight) / Time (days)]
- Feed conversion ratio (FCR) = Feed provided (g) / Weight gain (g)
- Survival rate (SR) (%) = 100 × (Final number of fish) / (Initial number of fish)

Physicochemical parameters

Monitoring environmental physicochemical parameters is crucial in assessing the health of aquatic ecosystems, particularly in relation to cage aquaculture. Key parameters such as dissolved oxygen (DO), temperature, pH, nitrite, nitrate, total phosphorus, ammonium, turbidity, and conductivity are essential indicators of water quality and nutrient levels. Water quality measurements and nutrient sampling were conducted monthly throughout the six-month experimental period. Many of these parameters were efficiently monitored using a YSI multi-parameter probe (556 MPS®). Specific nutrient analyses (nitrite, nitrate, total phosphorus, ammonium) were conducted using spectrophotometric methods (Shimadzu UV-1800) following standard protocols [13].

Nitrite was determined using the diazotization method. Powdered pillow reagent (100 mg) containing copper sulphate, sulphanilamide, potassium nitrate, hydrochloric acid, and N-(1-naphthyl)-ethylene diamine-dihydrochloride was added to a sample cell with 10 mL of sampled water. The mixture was swirled vigorously for 3 minutes and left for 10 minutes for reaction completion until a pink color appeared. Absorbance was read at 543 nm.

Nitrate was determined using the cadmium reduction method. Nitriver 3 nitrate reagent powder pillow (100 mg) was added to 10 mL of sampled water. After color development, the mixture was passed through a reduction column made of cadmium-copper filling. Absorbance was read at 543 nm.

Total Phosphorus (TP) was determined using the ascorbic acid method. For analysis, 25 mL of unfiltered sample was mixed with 5 mL potassium persulphate and autoclaved at 120°C for 30 minutes. After cooling, the mixed reagent (ammonium molybdate, sulphuric acid, ascorbic acid, potassium antimonyl tartrate) was added, and absorbance was measured at 885 nm.

Ammonium was determined using the colorimetric indophenol blue method. Powdered pillow reagent (100 mg) containing sodium nitroprusside, trisodium citrate dihydrate, sodium hydroxide, and phenol indicator was added to 10 mL of sampled water. Absorbance was read at 630 nm.

Statistical analysis

Statistical analyses were performed using SPSS version 23 for Windows. Two-way analysis of variance (ANOVA) was used to compare growth performance (weight, length, SGR, FCR) among species and to assess water quality parameters between cage sites and control sites over time. When significant differences were detected, post-hoc comparisons were conducted using Tukey's Honestly Significant Difference (HSD) test. Significance was set at $\alpha = 0.05$. Results are presented as means ± standard deviation (SD). Graphs were plotted using Microsoft Excel 2010.

Results

Growth performance and survival

Growth performance differed significantly among the three tilapia species under cage culture conditions (two-way ANOVA, species effect: $F_{(2, 24)} = 124.7$, $p < 0.001$). *Oreochromis niloticus* attained a mean final harvest weight of 185.39 ± 0.93 g after six months, which was significantly higher than both *O. variabilis* (47.26 ± 5.25 g) and *O. esculentus* (46.03 ± 1.99 g) (Tukey's HSD, $p < 0.001$ for both comparisons). No significant difference in final weight was detected between the two native species (Tukey's HSD, $p = 0.892$).

Body weight gain, monthly growth rate, and specific growth rate (SGR) all showed significant species effects ($p < 0.001$ for all). Feed conversion ratio (FCR) differed significantly among species ($F_{(2, 24)} = 98.3$), $p < 0.001$), with *O. niloticus* exhibiting a superior (lower) FCR of 1.77 compared to 5.26 for *O. variabilis* and 5.48 for *O. esculentus* (Tukey's HSD, $p < 0.001$) for both comparisons. The FCR did not differ significantly between the two native species (Tukey's HSD, $p = 0.764$). Survival rates were relatively high across all species. There was no significant difference in survival between *O. niloticus* (88.55%) and *O. esculentus* (85.55%) (Tukey's HSD, $p = 0.342$), but *O. variabilis* (75.9%) showed significantly lower survival than *O. niloticus* (Tukey's HSD, $p = 0.018$). Survival did not differ significantly between *O. variabilis* and *O. esculentus* (Tukey's HSD, $p = 0.097$).

Fry were consistently observed in the cages of both native species, *Oreochromis esculentus* and *Oreochromis variabilis*, during the culture period, indicating successful natural spawning and recruitment under cage conditions. The first occurrence of fry was recorded in *O. esculentus* in the third month of the experiment, followed by *O. variabilis* in the fourth month. Additionally, females of both species were frequently observed carrying eggs in their buccal cavities, confirming active mouthbrooding behavior and ongoing reproduction within the cages. The simultaneous presence of eggs and free-swimming fry demonstrates continuous breeding activity and successful early life-stage survival. In contrast, no fry or mouthbrooding females were observed in the *Oreochromis niloticus* cages throughout the study period (Table 1).

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The weight growth curve for *O. niloticus* showed a steep, nearly linear increase throughout the experimental period, reflecting rapid and consistent biomass accumulation. In contrast, the growth curves for the two native species were considerably flatter, with much slower monthly weight increments. By the end of the sixth month, the final mean weight of *O. niloticus* was approximately four times higher than that of either native species. The divergence between *O. niloticus* and the native species became evident from the second month and widened progressively, confirming the significant species effect on growth performance.

The length growth patterns followed a similar trend to the weight curves. *O. niloticus* displayed a strong and steady increase in total length, achieving substantially larger sizes by the end of the trial. The native species exhibited slower length gains, resulting in noticeably smaller final lengths.

Water quality parameters

Physicochemical parameters (dissolved oxygen, temperature, pH, conductivity, total dissolved solids, salinity) showed no significant differences between cage sites and open water controls (two-way ANOVA, location effect: $p > 0.05$ for all parameters; Table 2). No significant interaction effects between location and time were detected for any physicochemical parameter ($p > 0.05$).

Nutrient concentrations differed significantly by location (cage vs. control) for total nitrogen (TN) and total phosphorus (TP) ($p < 0.05$) (Table 3). Total nitrogen was significantly elevated in cage units ($F_{(3, 32)} = 8.67$), ($p = 0.002$), with the highest concentration recorded in *O. variabilis* cages (463.5 ± 54.7 µg L^{-1}). Pairwise comparisons revealed that TN in *O. variabilis* cages was significantly higher than in open water controls (Tukey's HSD, ($p = 0.008$) and significantly higher than in *O. niloticus* cages (Tukey's HSD, ($p = 0.011$). No other pairwise differences in TN were significant ($p > 0.05$).

Table 1: Growth performance and survival of *Oreochromis niloticus* (ON), *O. variabilis* (OV), and *O. esculentus* (OE) under cage culture conditions over six months. Values are means ± SD. Within each row, different superscript letters indicate significant differences between species (Tukey's HSD post-hoc test, $p<0.05$).

Parameter	ON	OV	OE	ANOVA p-value
Initial fingerling quantity	2000	2000	2000	-
Final fish quantity	1771	1518	1711	-
Initial weight (g)	6.9	5.9	8.2	-
Final harvest weight (g)	185.39 ± 0.93 [a]	47.26 ± 5.25 [b]	46.03 ± 1.99 [b]	<0.001
Body weight gain (g)	178.49 [a]	41.36 [b]	37.83 [b]	<0.001
Growth rate (g $month^{-1}$)	29.75 [a]	6.89 [b]	6.31 [b]	<0.001
Specific growth rate (SGR, % day^{-1})	1.83[a]	1.16 [b]	0.96 [b]	<0.001
Feed conversion ratio (FCR)	1.77[a]	5.26 [b]	5.48 [b]	<0.001
Survival rate (%)	88.55[a]	75.9 [b]	85.55 [a,b]	0.018

Note: Different superscript letters (a, b) within a row indicate significant differences at $p<0.05$ (Tukey's HSD). [a, b] indicates no significant difference from either group.

Table 2: Physicochemical parameters measured at cage sites (ON, OE, and OV) and open water control sites. Values are means ± SD. No significant differences were detected among locations for any parameter (two-way ANOVA, location effect: $p > 0.05$ for all).

Parameter	Unit	*O. niloticus* Cage	*O. esculentus* Cage	*O. variabilis* Cage	Open Water (Control)
DO	mg L^{-1}	8.01 ± 0.52	8.24 ± 0.48	8.43 ± 0.57	8.12 ± 0.67
Temperature	°C	25.54 ± 0.65	25.79 ± 0.71	25.92 ± 0.68	25.98 ± 0.72
pH	-	7.89 ± 0.41	7.92 ± 0.38	7.95 ± 0.44	7.84 ± 0.52
Conductivity	µS cm^{-1}	110.2 ± 1.03	110.6 ± 1.14	110.8 ± 1.22	110.4 ± 1.18
TDS	mg L^{-1}	70.8 ± 0.63	70.9 ± 0.74	71.1 ± 0.69	70.6 ± 0.81
Salinity	-	0.05 ± 0.00	0.05 ± 0.00	0.05 ± 0.00	0.05 ± 0.00

Total phosphorus also differed significantly among locations ($F_{(3, 32)} = 5.92$), ($p = 0.031$), with the highest concentration in *O. niloticus* cages (41.5 ± 2.2 µg L^{-1}). TP in *O. niloticus* cages was significantly higher than in *O. variabilis* cages (Tukey's HSD, ($p = 0.042$) and marginally higher than in open water controls (Tukey's HSD, ($p = 0.058$). No significant differences in TP were detected between *O. esculentus* cages and any other location ($p > 0.05$).

No significant differences among locations were detected for nitrate (NO_3), nitrite (NO_2), soluble reactive phosphorus (SRP), silica (SiO_2), ammonium (NH_4), chlorophyll-a (Chl-a), alkalinity (ALK), or total hardness ($p > 0.05$) for all; Table 3).

Discussion

This study evaluated the potential of cage aquaculture to support the conservation of two endangered native tilapiine cichlids, *Oreochromis variabilis* and *Oreochromis esculentus*, in Lake Victoria. Although *O. niloticus* remains superior for commercial production [14,15], our findings demonstrate that cage systems can function as effective ex-situ conservation tools, particularly for captive breeding and stock enhancement when species-specific management is applied. Central to this potential is the ability of native species not only to survive but also to reproduce under cage conditions.

Both native species exhibited relatively high survival (75.9–85.5%), consistent with previous studies [16,17]. Importantly, continuous fry occurrence confirms that *O. variabilis* and *O. esculentus* completed their reproductive cycles within cages. Fry appeared earlier in *O. esculentus* (month 3) than in *O. variabilis* (month 4), suggesting interspecific differences in reproductive timing or adaptation to culture conditions. The frequent observation of females carrying eggs in their buccal cavities confirms active maternal mouthbrooding, while the concurrent presence of eggs and free-swimming fry indicates overlapping spawning cycles and successful early-stage survival. These findings provide clear evidence that cage systems can support natural reproduction without hatchery intervention. This reproductive capacity directly underpins the conservation relevance of these systems.

The demonstrated in-cage spawning has important conservation implications. Cage systems can act as semi-controlled breeding refugia capable of generating seed stock

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Table 3: Nutrient concentrations and related water quality parameters measured at cage sites (ON, OE, OV) and open water control sites. Values are means ± SD. Different superscript letters within a row indicate significant differences between locations (Tukey's HSD post-hoc test, $p < 0.05$).

Parameter	Unit	ON Cage	OE Cage	OV Cage	Open Water	ANOVA p-value
Total phosphorus (TP)	µg L^{-1}	41.5 ± 2.2^{a}	29.9 ± 7.3^{a,b}	25.9 ± 12.5b	39.3 ± 14.7^{a,b}	0.031
Total nitrogen (TN)	µg L^{-1}	100.7 ± 58.6^{b}	214.7 ± 56.8^{a,b}	463.5 ± 54.7^{a}	311.0 ± 172.9^{a,b}	0.002
Nitrate (NO_3)	µg L^{-1}	4.4 ± 1.3	4.7 ± 1.6	6.4 ± 6.9	4.4 ± 1.6	0.624
Nitrite (NO_2)	µg L^{-1}	2.5 ± 0.8	1.9 ± 1.8	1.4 ± 0.9	1.7 ± 1.3	0.452
Soluble reactive phosphorus (SRP)	µg L^{-1}	25.6 ± 4.9	29.8 ± 9.5	34.1 ± 6.5	33.6 ± 8.8	0.187
Silica (SiO_2)	mg L^{-1}	2.8 ± 0.2	2.8 ± 0.2	2.6 ± 0.5	3.0 ± 0.8	0.538
Ammonium (NH_4)	µg L^{-1}	36.0 ± 41.9	36.7 ± 34.0	27.2 ± 32.0	20.9 ± 22.2	0.723
Chlorophyll-a (Chl-a)	mg L^{-1}	3.0 ± 1.6	2.7 ± 2.0	4.8 ± 2.1	3.4 ± 2.8	0.344
Alkalinity (ALK)	mg L^{-1}	37.1 ± 7.0	46.3 ± 22.4	32.3 ± 2.5	35.3 ± 6.0	0.294
Total hardness	mg L^{-1}	35.7 ± 8.9	34.0 ± 3.3	36.3 ± 3.8	32.9 ± 5.1	0.678

for restocking depleted populations. Given the documented declines of native tilapiines in Lake Victoria due to introduced species, overfishing, and hybridization [5,6], such systems could serve as genetic reservoirs and support reintroduction efforts [15]. The ability to produce fry continuously within relatively small cage units further strengthens their applicability for conservation-oriented aquaculture. However, the practical implementation of such systems depends not only on reproductive success but also on acceptable growth performance and production efficiency.

Despite successful reproduction, native species exhibited significantly lower growth performance and poor feed conversion ratios (FCR: 5.26–5.48 vs. 1.77 for *O. niloticus*; $p < 0.001$), likely due to the use of commercial diets formulated for *O. niloticus*. These diets may not match the nutritional requirements or feeding ecology of *O. variabilis* and *O. esculentus*. Rather than indicating unsuitability for aquaculture, this highlights the need for species-specific feed development. Future efforts should prioritize tailored diet formulation and selective breeding programs to improve growth while maintaining genetic integrity [8,9]. In parallel with biological performance, environmental sustainability remains a critical consideration for scaling conservation aquaculture systems.

Water quality results showed localized nutrient enrichment, with elevated total nitrogen and phosphorus at cage sites, consistent with previous observations in Lake Victoria [5,18]. Although levels remained below acute toxicity thresholds, they indicate potential long-term eutrophication risks. Conservation-oriented cage systems should therefore adopt stricter environmental controls, including optimized siting, reduced stocking densities, improved feed efficiency, and routine nutrient monitoring to minimize ecological impacts. Taken together, these biological and environmental considerations inform how cage aquaculture can be strategically integrated into broader fisheries management.

Overall, these findings support a dual aquaculture strategy: continued reliance on *O. niloticus* for commercial production, alongside the development of conservation-focused cage systems for native tilapiines. The demonstrated ability of *O. esculentus* and *O. variabilis* to reproduce naturally in cages highlights their potential for captive propagation, genetic conservation, and restocking programs. However, effective implementation will require integrated management approaches that incorporate nutrition, environmental sustainability, and genetic monitoring. To fully realize this potential, remaining knowledge gaps must be addressed through targeted research.

This study is limited by its six-month duration, single-site design, and use of one feed type. Future research should include longer-term, multi-site trials, evaluation of post-release survival, assessment of genetic and disease risks, and development of species-specific feeds and breeding programs [19-24].

Conclusion

This study demonstrates that cage aquaculture can support the ex-situ conservation of endangered native tilapiine cichlids in Lake Victoria by enabling survival, captive breeding, and continuous natural reproduction under controlled conditions. While growth performance of O. variabilis and O. esculentus remained substantially lower than that of O. niloticus under standard commercial feeding regimes, the observed reproductive success highlights the potential of cage systems as conservation and stock enhancement tools. Future research should prioritize selective breeding, species-specific feed formulation, genetic characterization, and long-term ecological monitoring to improve production efficiency while safeguarding ecosystem integrity.

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Author contributions

Tonny Orina Sagwe: Conceptualization, methodology, data collection, formal analysis, investigation, writing—original draft preparation, and manuscript revision. Robert Nesta Kagali: Supervision, methodology, manuscript review, and editing. Kevin Mbogo: Laboratory analysis, methodology, and manuscript review. Michael S. Cooperman: Project support, funding acquisition, and manuscript review. Les Kaufman: Conceptualization, supervision, manuscript review, and editing. John Okechi: Methodology, supervision, manuscript review, and editing. Paul Sagwe Orina: Field support, sampling coordination, and manuscript review. Mercy Chepkirui: Hatchery management, broodstock handling, and manuscript review.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

Ethical considerations

Ethical approval for this study was obtained from the Kenya Marine and Fisheries Research Institute. All procedures involving fish handling, transportation, breeding, sampling, and cage culture operations were conducted in accordance with institutional guidelines for the care and use of aquatic organisms in research. Efforts were made to minimize stress and mortality during handling and experimental procedures.

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