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Influence of net cages on water quality and trophic status of Lake Victoria, Kenya: The case of Kadimu Bay

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Abstract

Water quality is a critical component regulating ecosystem functioning in aquatic habitats, requiring regular monitoring for sustainable ecosystem services. Cage fish farming has the potential to affect water quality because of its rapid increase in many African waterbodies in response to dwindling wild fish stocks. Thus, there is a need for more studies to guide sustainable cage aquaculture in African lakes and reservoirs. This study evaluated the possible effects of cage farming of Nile tilapia (*Oreochromis niloticus*) on water quality parameters and the trophic state of Kadimu Bay, Lake Victoria, Kenya. Sampling for physicochemical and biological variables, including nutrient load, was conducted from January to October 2021, at five fish cage sites and a control site within the bay. In situ measurements of physical variables were undertaken in the field, while analysis of water samples for nutrient loads, biological and chemical variables was undertaken in the laboratory, following the methods described in APHA (*American public health association standard methods for the examination of water and waste water.* APHA-AWWA-WEF, 2005). The Carlson's Trophic State Index (CTSI) was used to classify the trophic state of the cage sites, while the total nitrogen:total phosphorus (TN:TP) ratio was used to determine the primary productivity limiting nutrient in the bay. The study results indicated electrical conductivity was significantly lower at the control (97.53 ± 4.17 μS/cm), compared to cage sites (105.42 ± 5.32 μS/cm at the Utonga cage site to 112.84 ± 1.94 μS/cm at the Oele cage site), indicating water of relatively lower quality at the cage sites. Similarly, the nitrite concentrations were higher at cage sites (6.35 ± .96 μg/L at the Uwaria cage site to 3.16 ± 2.25 μg/L at the Utonga cage site), and lower at the control site (2.68 ± 1.39 μg/L). In all, 14 physicochemical variables did not vary significantly between the cage and control sites, with nine variables (temperature, turbidity, electrical conductivity, total suspended solids, particulate organic matter, chlorophyll-a, TP, nitrate and TN) being within the recommended thresholds for aquatic life processes. The bay was evaluated as being in a light eutrophic state, indicating moderate influence of the fish cages on the trophic state of the sites. There was a moderate relationship between chlorophyll-a and TP concentration at the sampling sites ($R^2 = .50$), compared to a stronger relationship with NO_3^- ($R^2 = .78$). The TN:TP ratios were <10 at the sampling sites, indicating nitrogen was the limiting factor for primary production in the bay. The calculated CTSI suggests that the bay exhibited a light eutrophic state. Overall, although the results of this study showed cage aquaculture is not a current challenge to the water quality of the bay, regular monitoring is nevertheless recommended to inform sustainable aquaculture development in the bay and lake.

KEYWORDS
aquaculture development, Carlson's Trophic Index, eutrophication, Nile tilapia, nutrient limitation

1 | INTRODUCTION

Cage fish farming in African inland aquatic ecosystems has the ability to close the gap between fish supply and demand deficit, and to improve other livelihood benefits such as poverty alleviation, employment opportunities and contribute to food security and gross domestic products (Musinguzi et al., 2019). Cage aquaculture has rapidly increased globally over the last decade (FAO, 2022). This proliferation is partly attributable to an increased demand for fish protein as wild fish stocks continue to dwindle because of over-exploitation (Moffitt & Cajas-Cano, 2014; Worm et al., 2006). Furthermore, cage aquaculture has a relatively low cost of investment, ease of installation maintenance and higher yield per volume of water relative to pond aquaculture (Beveridge, 1984; Gentry et al., 2017; Musinguzi et al., 2019). Lakes Victoria, Kariba and Volta and the Volta River host 82.9% of cage installations on African inland waters and represent major areas for cage aquaculture (Aura et al., 2018; Musinguzi et al., 2019). It is reported that there were ca. 4400 fish cages in 2020 covering ca. 62,100 m^2 of Lake Victoria, with the number predicted to increase with time (Aura, 2020). Despite the increasing use of fish cages in African lakes and reservoirs, there are few regulations and management protocols focusing on sustainable aquaculture production within the framework of an ecosystem approach to fisheries management (Clottey et al., 2016; Frankic & Hershner, 2003). Cage aquaculture management requires the provision of scientific data on water quality variability, feeding regimes and stocking densities, in addition to socio-economic information aimed at minimizing user conflicts.

Water quality monitoring and assessment programmes at cage aquaculture sites are necessary to inform public policies on aquaculture production in natural aquatic systems (Aura et al., 2017). Water quality is a critical determinant of ecosystem structure and functioning because of its influence on productivity, physiological and behavioural activities of aquatic organisms (Scheffer et al., 2001), and species abundance (Wootton, 1991). Cage aquaculture has the potential to affect the water quality of aquatic ecosystems through uneaten fish feed and wastes, with the likelihood of causing eutrophication impacts (Pillay & Kutty, 2005). Uneaten feed and fish wastes contribute to phosphorous and nitrogen enrichment, ultimately leading to eutrophication impacts such as reduced turbidity attributable to algal biomass and deoxygenation with the potential for fish kills and loss of biodiversity (Ngupula & Kayanda, 2010; Sayer et al., 2016; Vollenweider et al., 1998). Total phosphorus (TP) has long been identified as the ultimate phytoplankton growth-limiting nutrient within freshwater ecosystems (the P paradigm sensu Schindler, 2012) leading to TP models of eutrophication management (Vollenweider, 1968). Accordingly, continuous water quality monitoring around aquaculture installations is required to advise on aquaculture development and management (Aura et al., 2018; Musinguzi et al., 2019). This is particularly the case for Lake Victoria, where aquaculture installations continue to increase rapidly without consistent environmental monitoring initiatives (Aura et al., 2017; Njiru et al., 2018), and where eutrophication remains a major challenge (Kolding et al., 2008). Furthermore, the extent to which the Lake Victoria ecosystem is limited by nutrients is not known and the addition of TP and total nitrogen (TN) through fish foods may affect the lake's nutrient balance (Beveridge, 1984) making it necessary to continuously evaluate the TP:TN ratios around fish cages.

There have been some studies reporting the effects of experimental fish cages on water quality in the Tanzanian portion of Lake Victoria (Kashindye et al., 2015). Nevertheless, studies documenting the effects of cage aquaculture on water quality and ecosystem functioning in African lakes are generally scarce. Accordingly, this study evaluates water quality variables within a shallow, high-density fish cage area (Kadimu Bay) in the Winam Gulf of Lake Victoria, and compares the values with the acceptable ranges for ecosystem functioning. Carlson's Trophic State Index (CTSI; Carlson & Simpson, 1976; Carlson, 1977) was used to evaluate the trophic state of the cage sites in the bay, and to test a hypothesis of cage influences on the bay's trophic state. This study also evaluated the relative TP and TN nutrient limitation of productivity in the bay, testing the commonly held notion of TP limitation in freshwater lakes (Schindler, 2012; Vollenweider, 1968).

2 | MATERIALS AND METHODS

2.1 | Study area

Lake Victoria is among Africa's great lakes, with a surface area of ca. 59,947 km^2 (Stuart, 2016). It is the largest lake in Africa by surface area, the world's largest tropical lake and second largest freshwater lake globally (Prado et al., 1991). It has an average depth of 40 m with a catchment area of 169,858 km^2 (Stuart et al., 2018). The lake is divided between three countries, including Kenya (6%), Uganda (45%) and Tanzania (49%) (Stuart et al., 2018).

This study was conducted within Kadimu Bay (Figure 1), one of the bays with active cage fish aquaculture on the Kenyan side of Lake Victoria. The bay is situated between latitude 0°6′0″ S and longitude 34°6′0″ E and lies at an elevation of 1133 m above sea level (Kottek et al., 2006). The depth range of Kadimu Bay is between 3 and 12 m, with an area of ca. 947 km^2, and spanning a distance of 4.3 km (Calamari et al., 1995). The shallow and sheltered nature of the bay makes it popular for cage fish farming. Unfortunately, however, shallow, protected bays are more susceptible to eutrophication and algal bloom impacts (McGlathery et al., 2007). The annual average precipitation around the lake basin is ca. 1300 mm with an average annual temperature of 22.9°C (Masongo et al., 2005). Most of the sheltered bays in Lake Victoria have cage fish farming as an intensive production system (Opiyo et al., 2018), with the cages in the lake ranging from small (2 × 2 × 2 m) to larger ones (10.5 × 5.0 × 2.5). The main cultured species is the Nile tilapia (*Oreochromis niloticus*) (Opiyo et al., 2018), which are fed commercial feed pellets supplemented with farmer-formulated feeds comprising freshwater shrimp (*Caridina nilotica*). Sampling was carried out at the sites with ongoing tilapia farming, and a control site located in an area within the bay that did not have cage installations (Figure 1).

2.2 | Sampling and analytical procedures

Sampling for physicochemical variables and biological parameters was conducted at five fish cage sites, and at a control site within Kadimu Bay. The control site (Figure 1) was removed from the cage area, had an average depth of 9.4-m and no fish cages, therefore considered a control for the influence of the cages on water quality, thereby allowing for statistical inference. The five cage sites are locally referred to as follows: Anyanga, Uwaria, Oele, Ugambe and Utonga (see Figure 1 for relative locations). The sites had an average depth of 9.08 m, being separated by an average distance of 1.4 km. Each cage site is managed under a different beach management unit (BMU). The sites were selected because they had ongoing cage fish farming activities and were easily accessible. Sampling for water quality variables was conducted from January to October 2021. Three replicate water samples were collected with a Van Dorn water sampler on each sampling trip at the same average depth across the sites. The samples were kept in a cooler box at a temperature of ca. 4°C and transported to the Kenya Marine and Fisheries Research Institute (KMFRI) laboratory for analysis of chlorophyll-a, TP, nitrates, nitrites and TN concentrations. Temperature, pH, dissolved oxygen (DO) and total dissolved solids (TDS) concentrations, turbidity and electrical conductivity (EC) were measured in situ with a Hanna multi-parameter probe (H9829). Water transparency was measured in situ with a Secchi disk (SD; 20 cm diameter) (Bartram & Balance, 1996). Sampling was conducted three times per site on a monthly basis for the 10 months of sampling. Thus, a total of 30 water samples were analysed for each of the five sites and the control point.

2.3 | Analytical procedures

Total suspended solids (TSS) and particulate organic matter (POM) were estimated by filtering 10 mg of sample water with GFC filters. Following weighing the filters to obtain their initial weight, the sample

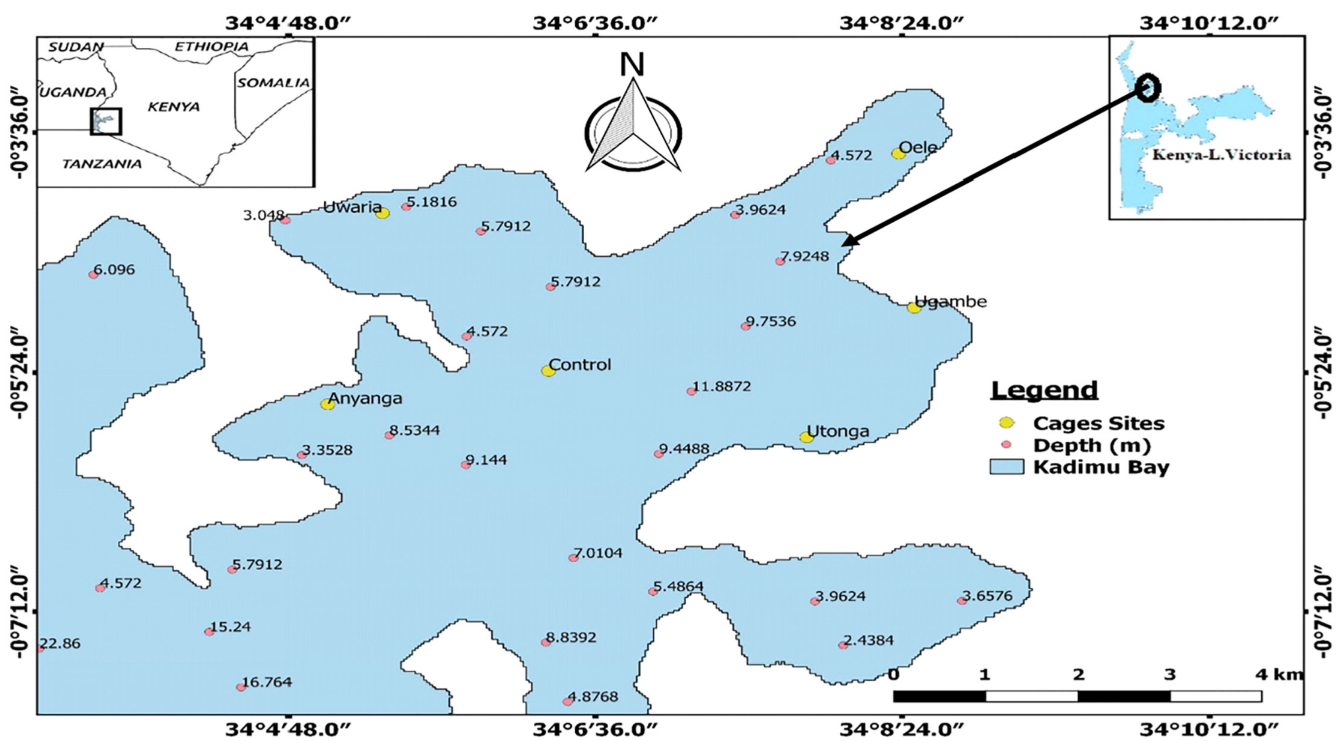

FIGURE 1 Map of Lake Victoria showing sampled cage sites (Anyanga, Uwaria, Oele, Ugambe, Utonga) in Kadimu Bay, Winam Gulf, Kenya (modified from KMFRI, 2020).

water was filtered through them and weighed to obtain the final weight. This was followed by oven drying and weighing to obtain the ash weight. The TSS concentration was estimated as the difference between the initial and final weights, while the POM concentration was estimated as the difference between the final weight and ash weights as per the procedures outlined by APHA (2005) and Rodier et al. (2009). The molybdenum blue procedure was used to estimate the soluble reactive phosphorus (SRP) concentration, while the dichloroisocyanurate-salicylate procedure was used to estimate the ammonium ion concentrations (APHA, 2005). The cadmium reduction procedure and the azo-dye complex technique were used to estimate the nitrate and nitrite concentrations by running sample water through a cadmium column filled with coated metallic copper (APHA, 2005). UV spectrophotometer (Genesys 10S Vis SN-2F1N308001) was used for analysis of the chlorophyll-a, TP and TN concentrations. Alkaline potassium persulphate was used to digest TP through a high temperature process, thereby converting all phosphorus compounds to orthophosphate and allowing it to react with molybdic acid and ascorbic acid, which is reduced to phosphomolybdae, and the absorption read at 885 nm (APHA, 2005). The same procedure was followed for analysis of the TN concentration. Partitioning of chlorophyll-a was done using the sonication technique, with the effective concentration determined with the Lorenzen equation (APHA, 2005) through the application of absorbance readings from the UV spectrophotometer (Rodier et al., 2009).

2.4 | Nutrient limitation and trophic state evaluation

Nutrient availability and limitation in the bay were evaluated using the TN:TP ratio (OECD, 1982; Reynolds, 1999). TN limitation was considered probable when the molar TN:TP ratio was <10, and TP limitation when the TN:TP ratio exceeded 20 (Maberly et al., 2020). Intermediate ratios indicated potential TN and TP co-limitation (Maberly et al., 2020). CTSI is based on TP chlorophyll-a (a measure of primary production) concentrations and SD transparency (Carlson, 1977). The suggested limits for designation of a trophic state were based on the recommendations in Carlson and Simpson (1976). The trophic state index (TSI) values are meant to describe the water quality state of the sampling sites by estimating the productivity exhibited as a function of the algal biomass. The algal biomass was calculated using empirical equations and applying the concentration of chlorophyll-a and TP values and the Secchi depth transparency (Carlson, 1977). The trophic state (TS) groupings based on the calculated CTSI values are presented in Table 1.

The TSI was calculated separately on the basis of the three individual parameters; namely chlorophyll-a (μg/L), TP (μg/L) and Secchi depth (m), with the overall CTSI for each site evaluated from the average of the three separate values as indicated by Carlson (1977), as follows:

$$\text{TSI (SD)} = 10\left(6 - \frac{\ln SD}{\ln 2}\right) \tag{1}$$

$$\text{TSI (Chl} - \text{a)} = 10\left(6 - \frac{2.04 - .68 \ln \text{Chl} - \text{a}}{\ln 2}\right) \tag{2}$$

$$\text{TSI (TP)} = 10\left(6 - \frac{\ln \frac{48}{TP}}{\ln 2}\right) \tag{3}$$

$$\text{Site CTSI} = \frac{\text{TSI (SD)} + \text{TSI (Chloro} - \text{a} + \text{TSI(TP))}}{3} \tag{4}$$

2.5 | Data treatment and statistical analysis

Water quality variables in the bay were evaluated using the national (Aura, 2020) and international (WHO, 2008, 2011) recommended limits for ecosystem functioning and services. Two-way analysis of variance was performed on log $(x+1)$ transformed data to test for significant differences in physicochemical variables and CTSI among the sites and sampling months as the main factors, and the interactions between sites and months. The mean values of the factors exhibiting significant effects ($p<.05$) were compared either between sites or months using one-way ANOVA and the Turkey–Kramer multiple comparison post hoc test to identify the significantly different variables within sites or months. Where monthly effects were significant (Table S1), the temporal pattern of variations of the variables was examined using a graphical plot. Log-transformation and Levene's test were used to test for normality and homoscedasticity assumptions of ANOVA (Zar, 1999). All graphical plots were implemented in the Sigma Plot software.

3 | RESULTS

3.1 | Water quality variables and standard limits

Most of the physicochemical variables measured during this study exhibited no significant differences between months or sites (Table S1). In all, 17 variables, including pH, DO, TDS, turbidity, electrical conductivity, POM, temperature, TSS, SRP, TN, TP, NO_2^-, NO_3^-, NH_3, NH_4^+, SiO_4^{4-} and chlorophyll-a were not significantly different between sampling months, whereas 14 variables, including temperature, pH, DO, turbidity, POM, NH_4^+, SiO_4^{4-}, TSS, SRP, TN, TP, TDS, NO_3^- and NH_3 also were not significantly different between sampling sites (Table S1). Only the chlorophyll-a and nitrite concentrations and electrical conductivity exhibited significant differences between sites but not between months (Table 2, Table S1). No significant interactions were observed between sites and months for all the studied variables. Electrical conductivity was significantly lower at the control site than for the fish cage areas, while the chlorophyll-a and nitrite concentrations were only significantly different for the control site, compared to the other sites (Table 2) following the Turkey–Kramer post hoc test.

The mean values of pH, temperature, TDS, TSS, chlorophyll-a, electrical conductivity, turbidity, nitrates, nitrites, TN and ammonium

TABLE 1 Carlson's trophic state classification scheme (Carlson, 1977) for classifying the trophic states of cage sites in Kadimu Bay, Lake Victoria, Kenya.

Carlson Trophic State Index (TSI)	Lake trophic state index	Attributes
<30	Ultra-oligotrophic	Clear water; oxygen in hypolimnion throughout annual cycle
30–40	Oligotrophic	Oligotrophy; but some shallow lakes may become anoxic during dry season
40–50	Mesotrophic	Water moderately clear, but increasing occurrence of anoxia during dry season
50–60	Mild eutrophic	Decrease transparency; warm water fisheries only
60–70	Medium eutrophic	Possibility of algae blooms during dry season, tending towards hypereutrophic state
70–80	Heavy eutrophic	Decreasing macrophyte species; occurrence of alga scum; loss of cultured fish
>80	Hypereutrophic	Increasing alga blooms; evident eutrophication of water

were all within the recommended thresholds for aquatic life at all sites (Table 2), indicating lack of a negative influence of the cages on these environmental conditions in the bay. The TP concentrations were moderately above the standard limit for aquatic life (50 µg/L), while the DO concentration exhibited no significant difference ($p > .05$) between sites, but did exceed the threshold limit (6.0 mg/L) recommended for aquatic life (Table 2).

For the three variables exhibiting differences between sites, nitrites exhibited a minimum value at the control site (2.68 ± 1.39 µg/L) and a maximum (6.35 ± .96 µg/L) at the Uwaria site, with an overall mean of 4.89 ± 1.39 µg/L among the six sites (Table 2). The electrical conductivity (an indirect measure of pollution) varied from a minimum of 97.53 ± 4.17 µS/cm at the control site to a peak of 112.84 ± 1.94 µS/cm at the Oele site, with an overall mean of 108.31 ± 4.55 µS/cm among sites. The chlorophyll-a concentration (a measure of aquatic productivity) exhibited a minimum value at the Anyanga site (1.71 ± .16 µg/L) and peaked at the Uwaria cage site (11.26 ± 4.80 µg/L), with an overall mean of 4.04 ± 2.99 µg/L among the sites. A Turkey–Kramer post hoc test indicated the electrical conductivity differed significantly only at the control site, while the chlorophyll-a and nitrite concentrations differed at the Uwaria and control site.

3.2 | Trophic state of sites

The five cage sites in the bay exhibited a mean (±SD) CTSI of 55.23 ± 2.04, ranging from 53.83 ± 14.02 at the Utonga site to 59.27 ± 12.36 at the Uwaria site (Table 3), suggesting a light eutrophic status of the sites, based on the thresholds shown in Table 1. The control site, removed from the cage sites, exhibited a CTSI value of 53.14 ± 12.08, also indicating a light eutrophic state similar to the cage sites. The CTSI values indicated the Uwaria cage site (see Figure 1 for site locations) had the highest index value, while the Utonga site had the lowest. A Turkey–Kramer post hoc test indicated the Uwaria site exhibited a significantly different CTSI value, but was indicative of a light eutrophic state (Table 3). Based on individual variable (chlorophyll-a; TP; Secchi depth) contributions to the overall CTSI, the TP contributed most to the CTSI values, with a mean trophic state based on TP ranging between 68.12 ± 2.07 and 73.39 ± 8.43 among the sampling sites. Secchi depth, a measure of water transparency, provided the second highest contribution to the CTSI of the sites, exhibiting TSI values ranging between 52.78 ± .83 and 54.17 ± .84 among the sampling sites (Table 3).

All the months exhibited a light eutrophic state, although some months exhibited a significantly different intensity of the eutrophic states from the others (Table 4). The overall CTSI exhibited a mean (±SD) of 54.67 ± 1.54, varying from 52.63 ± 13.53 in July to a peak of 57.49 ± 10.85 in March. The bay CTSI was significantly lower in February, April and July, based on the Turkey–Kramer post hoc test. The contribution of the Secchi depth transparency to the CTSI was not significantly different between the sampling months (Table 4), although the chlorophyll-a and TP contributions varied between the months. The chlorophyll-a contribution to the monthly trophic states of the bay (TSI Chl-a) was significantly different and lower during April–July, while the TP contribution (TSITP) was only significantly different and higher in January and March (Table 4).

3.3 | Relationship between chlorophyll-a, TP and nitrate concentrations

The relationship between the chlorophyll-a (Chl-a), TP and nitrate (NO_3^-) concentrations for all sites combined is illustrated in Figure 2. There was a moderate relationship between their concentration at the sites ($R^2 = .50$), possibly indicating a less strong limitation of TP on the chlorophyll-a abundance in the bay. The nitrate concentrations exhibited a relatively stronger relationship with chlorophyll-a in the bay ($R^2 = .78$). The site-specific relationship between the chlorophyll-a and TP concentrations in the bay exhibited a strong, nearly uniform relationship ($R^2 = .68$–$.92$; Figure 3). A similar, but stronger, relationship was noted the nitrate and chlorophyll-a concentrations for the sites in the bay ($R^2 = .59$–$.95$; Figure 3). There was a stronger relationship between the Chl-a and TP levels ($R^2 = .72$) than with nitrates ($R^2 = .59$) for the control site.

3.4 | TN:TP ratios

The TN concentration (mean ± SD) ranged from a minimum of 276.17 ± 54.64 µg/L at the Uwaria site to a maximum of

TABLE 2 Statistical summary of physicochemical parameters of cage sites in Kadimu Bay, Lake Victoria (Kenya), January–October 2021 (bold figures represent variables significantly different [$p < .05$] between sites; values represent mean ± SD; means with different letters across sites are significantly different).

Parameter/ site	Anyanga	Oele	Uwaria	Ugambe	Utonga	Control	ANOVA F	ANOVA p	Standard for aquatic life
DO (µg/L)	7.06 ± .61	7.25 ± .56	7.58 ± .45	7.29 ± .93	6.78 ± 1.32	7.67 ± .46	.37	.861	6[1,2,3,4]
Temp (°C)	26.61 ± .87	26.65 ± .81	26.63 ± .80	26.60 ± .65	26.72 ± .88	26.70 ± .95	.18	.965	
Acidity (H^+)	7.63 ± .19	7.63 ± .24	7.72 ± .28	7.78 ± .57	7.88 ± .52	7.71 ± .24	.94	.482	6.5–9.0[1,2,3]
TDS (µg/L)	65.9 ± 4.16	66.9 ± 3.33	65.8 ± 5.05	66.2 ± 4.12	63.9 ± 5.20	66.89 ± 3.74	1.33	.303	500[1]
Turb. (FMU)	3.56 ± 1.44	3.43 ± 1.44	3.86 ± 1.67	3.80 ± 1.13	3.33 ± 1.08	1.95 ± .83	.26	.930	5[1]
EC (µs/cm)	**110.31 ± 1.62^{A}**	**112.84 ± 1.94^{A}**	**110.09 ± 2.27^{A}**	**107.47 ± 5.70^{A}**	**105.42 ± 5.32^{A}**	**97.53 ± 4.17^{B}**	9.91	.000	1500[3]
TSS (µg/L)	4.87 ± .37	4.91 ± .64	4.25 ± .76	4.71 ± 1.12	4.25 ± .46	3.43 ± .97	1.46	.259	<30[1,2,3,4]
POM (µg/L)	1.99 ± .16	1.84 ± .24	1.57 ± .15	1.88 ± .24	1.64 ± .14	1.65 ± .33	1.17	.369	
Chl-a (µg/L)	**1.71 ± .16^{B}**	**2.13 ± .84^{B}**	**11.26 ± 4.80^{A}**	**2.99 ± 2.56^{B}**	**2.69 ± 1.31^{B}**	**2.22 ± .63^{B}**	4.78	.008	<12[1,2]
SRP (µg/L)	15.6 ± 4.0	17.07 ± 6.55	19.7 ± 8.47	17.1 ± 7.59	12.6 ± 3.82	10.84 ± 1.42	1.01	.448	
NO_3^- (µg/L)	7.35 ± 2.82	10.09 ± 1.67	7.54 ± 1.43	7.72 ± 3.84	7.80 ± 2.79	7.53 ± 1.09	2.63	.067	<1000[1,4]
NO_2^- (µg/L)	**5.45 ± 1.30^{AB}**	**5.34 ± 1.16^{AB}**	**6.35 ± .96^{A}**	**5.62 ± .63^{AB}**	**3.16 ± 2.25^{AB}**	**2.68 ± 1.39^{B}**	4.18	.014	<100[1,4]
TN (µg/L)	332.54 ± 26.0	344.36 ± 29.6	277.55 ± 49.3	349.71 ± 37.43	335.51 ± 21.7	254.67 ± 31.93	1.88	.158	4000[5,6]
TP (µg/L)	86.79 ± 2.20	108.77 ± 46.6	121.08 ± 50.59	96.29 ± 23.5	84.19 ± 8.65	78.22 ± 8.55	1.30	.315	50[4,5,6]
NH_3 (µg/L)	21.89 ± 6.77	20.46 ± 8.32	22.84 ± 10.63	18.80 ± 3.28	18.70 ± 4.73	19.13 ± 5.46	.03	.999	<10–1150[7]
NH_4^+ (µg/L)	17.44 ± 3.75	24.14 ± 8.38	18.60 ± 3.90	19.48 ± 4.13	18.22 ± 2.65	16.93 ± 2.13	.75	.596	<1000[1,4]
SiO_4^{4-} (mg/L)	13.26 ± 1.04	15.14 ± 1.60	14.75 ± 2.04	15.55 ± 1.34	13.96 ± 2.81	13.44 ± 1.88	2.37	.054	

Note: Abbreviations of parameters as shown in text.

Sources: [1]CCME (2009); [2]APHA (2005); [3]Rodier et al. (2009); [4]ANZECC (2000); [5]Philips et al. (2018); [6]Poikane et al. (2019); [7]Eglal et al. (2009).

TABLE 3 Carlson Trophic State Index (CTSI) and Trophic State Index (TSI) values of variables at cage sites in Kadimu Bay, Lake Victoria, Kenya (means values across sites with different letters exhibit significant difference; ±, SDs).

	Cage sampling sites						Tukey–Kramer	
Parameters	Anyanga	Uwaria	Oele	Ugambe	Utonga	Control	*F*	*p*
TSI (Chl-a)	40.54 ± 5.51^{b}	50.40 ± 7.34^{a}	40.68 ± 4.96^{b}	40.19 ± 3.84^{b}	40.09 ± 3.52^{b}	38.00 ± 3.82^{b}	**16.99**	**.000**
TSI (SD)	53.45 ± 1.21	54.02 ± 1.44	$54.17 \pm .84$	$52.78 \pm .83$	53.28 ± 1.52	53.84 ± 1.36	.95	.454
TSI (TP)	$68.47 \pm .44^{b}$	73.39 ± 8.43^{a}	69.43 ± 1.60^{b}	69.43 ± 1.78^{b}	68.12 ± 2.07^{b}	67.57 ± 1.11^{b}	**5.98**	**.000**
CTSI	54.15 ± 13.98^{b}	59.27 ± 12.36^{a}	54.76 ± 14.38^{b}	54.13 ± 14.67^{b}	53.83 ± 14.02^{b}	53.14 ± 12.08^{b}	**9.93**	**.000**
Trophic status	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic		

Note: Parameter abbreviations as shown in text.

Abbreviations: Chl-a, chlorophyll-a; CTSI, Carlson Trophic State Index; SD, Secchi depth; TP, total phosphorus.

TABLE 4 Carlson Trophic State Index (CTSI) values and Trophic State Index (TSI) values of variables for sampling months in Kadimu Bay, Lake Victoria, Kenya (mean values [±SD] across months with different letters exhibit significant difference).

		Sampling months									Tukey–Kramer	
Parameters	January	February	March	April	May	June	July	August	September	October	*F*	*p*
TSI (Chl-a)	42.11 ± 11.74^{a}	42.92 ± 1.41^{a}	46.46 ± 7.84^{a}	36.98 ± 1.12^{b}	39.12 ± 2.12^{b}	41.22 ± 10.05^{b}	35.72 ± 3.55^{b}	46.34 ± 2.49^{a}	42.42 ± 2.39^{a}	$42.47 \pm .56^{a}$	18.84	.000
TSI (SD)	$54.18 \pm .79$	52.97 ± 1.08	53.78 ± 1.05	52.97 ± 1.08	$53.04 \pm .07$	53.11 ± 2.29	53.30 ± 1.47	$53.24 \pm .73$	53.88 ± 1.16	$54.19 \pm .78$	.96	.343
TSI (TP)	73.73 ± 6.76^{a}	67.87 ± 2.39^{b}	72.25 ± 6.87^{a}	68.58 ± 1.13^{b}	$68.76 \pm .18^{b}$	68.94 ± 1.36^{b}	68.86 ± 1.42^{b}	$68.25 \pm .72^{b}$	67.64 ± 1.24^{b}	$68.67 \pm .16^{b}$	.83	.000
CTSI	56.67 ± 13.02^{a}	52.59 ± 10.25^{c}	57.49 ± 10.85^{a}	52.84 ± 12.90^{c}	53.64 ± 12.11^{b}	53.42 ± 11.35^{b}	52.63 ± 13.53^{c}	55.94 ± 9.15^{b}	54.65 ± 10.31^{b}	54.78 ± 11.11^{b}	8.44	.000
Trophic status	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic		

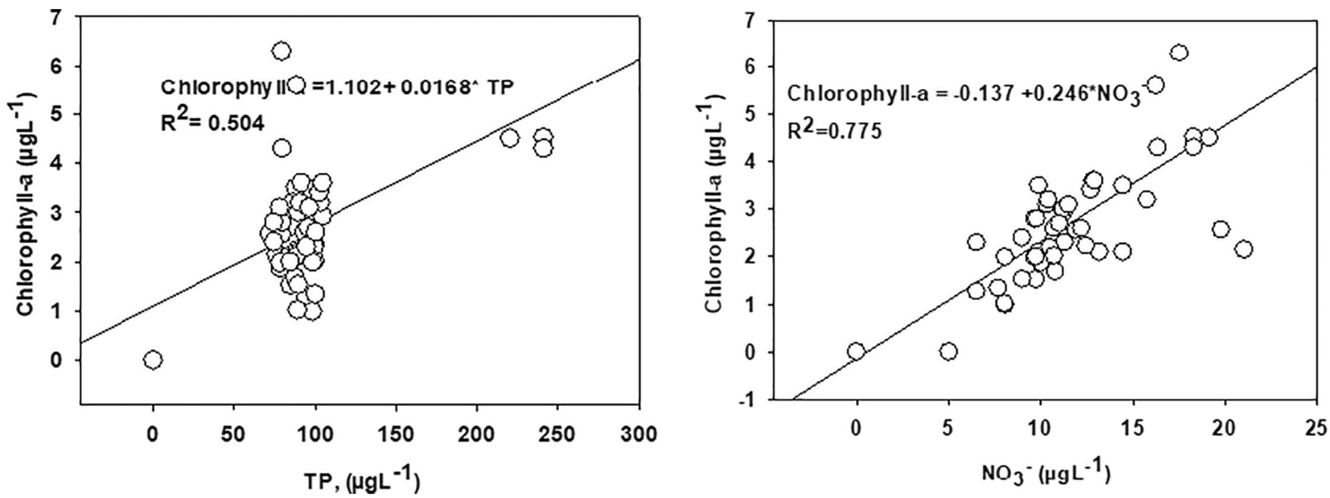

FIGURE 2 Relationship between chlorophyll-a, total phosphorus (TP) and nitrate (NO_3^-) concentrations for all cage sites in Kadimu Bay of Lake Victoria, Kenya, January–October 2021.

353.69 ± 26.98 μg/L at the Ugambe site (Table 5), while the TP concentration was lowest at the Utonga site (85.11 ± 10.51 μg/L) and highest at the Uwaria site (140.02 ± 24.43 μg/L; Table 5). The TN:TP ratio (a measure of nutrient limitation on primary production) ranged from a minimum of 1.97 at the Uwaria site to a maximum of 3.93 at the Utonga site, suggesting a strong limitation of TN, rather than TP (TN:TP < 10), in the bay.

4 | DISCUSSION

4.1 | Water quality variables and standard limits

This study evaluated the water quality and trophic states attributable to fish cage sites in Kadimu Bay, Lake Victoria (Kenya) to generate information applicable for sustainable aquaculture production and development in the lake. Nearly all the water quality variables exhibited no significant differences between cage sites, except for the chlorophyll-a and nitrite concentrations and the electrical conductivity. The values of the variables were highest at the cage sites for the nitrite and chlorophyll-a concentrations and electrical conductivity, relative to the control area, which contained no cages, thereby suggesting an influence of cage aquaculture on the water quality and primary productivity in the bay. The nutrients attributable from fish food likely enhanced the productivity and the electrical conductivity (a measure of pollution) in the bay (Pillay & Kutty, 2005). Although the bay exhibited a light eutrophic state, based on its CTSI, increasing electrical conductivity and algal biomass (measured by Chl-a) values suggest the possibility of the bay tipping over to eutrophication impacts if not properly monitored (Gikuma-Njuru et al., 2021; Wetzel, 2001). Noting the three significant variables are important for ecosystem metabolism (Hu et al., 2015), there is need for a more holistic management of the bay and the lake, integrating watershed management and aquaculture production (Musinguzi et al., 2019). Other studies (Kolding et al., 2008) suggested eutrophication was a greater challenge to Lake Victoria fisheries than overfishing. Eutrophication threats, however, are likely to be area and season specific and depend on depth profiles, watershed management and perhaps the intensity of cage aquaculture in the lake.

The DO concentrations for all the cage sites were higher than the recommended minimum standard limit of 6 mg/L for aquatic life (APHA, 2005; Rodier et al., 2009), suggesting adequate aeration and perhaps little influence of decomposing fish food on the DO levels. The decomposition of leftover food and wastes can lead to excessive deoxygenation of the water column, with such negative consequences as fish kills or reduced benthic biodiversity (Beveridge, 1984). Many measured water quality parameters, including acidity, total dissolved solids, turbidity, electrical conductivity, TSSs, nitrates, nitrites, TN, ammonia and ammonium ion concentrations were within the recommended standard limits for aquatic life, indicating less influence of the aquaculture activities on the ionic composition of the water and, in turn, on the ecological functioning of the bay. Similar findings were reported for cage fish farming on the Tanzanian side of Lake Victoria, being attributable to water movements (Kashindye et al., 2015). The cage sites in Kadimu Bay exhibited significantly lower values for some parameters (TDS and DO) and higher for others (electrical conductivity, turbidity, nitrites, TN, TP, ammonia and ammonium ions) relative to the control site, suggesting a potential influence of caging on these parameters if the bay tipping points are passed (Degefu et al., 2021; Gikuma-Njuru et al., 2021), thereby justifying the need for regular monitoring of environmental quality changes.

4.2 | Trophic state of sites

The derived CTSI values indicated a light eutrophic state of the lake water around the cage sites, implying eutrophication is not currently a major threat to fish cage aquaculture in the bay. The same trophic state was observed for the control site suggesting a bay-wide trophic

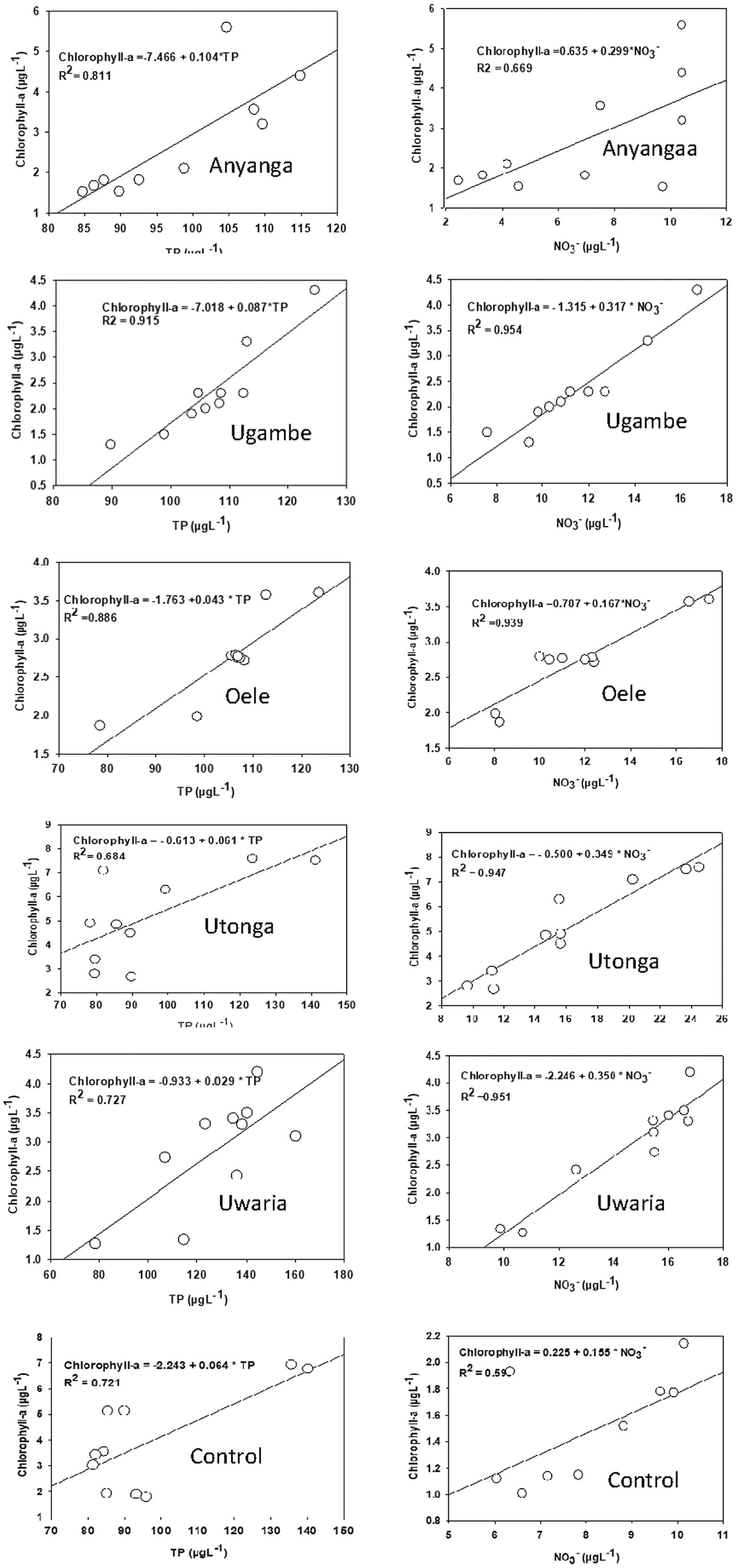

FIGURE 3 Site-specific relationship between chlorophyll-a, total phosphorus (TP) and nitrate (NO_3^-) concentrations in Kadimu Bay of Lake Victoria, Kenya, January–October 2021.

state that may not be solely attributable to the fish cage activities. The TP concentration contributed most to the calculated CTSI values, followed by Secchi depth (a measure of turbidity), implying a need to monitor TP inputs into the bay and to prevent a possible phase shift to algal blooms with its many negative consequences (Masser, 2008). According to Mahmuti et al. (2019), trophic states

Site	TN (μg/L)	TP (μg/L)	TN:TP ratio	Limiting nutrient
Anyanga	332.92 ± 27.22	86.53 ± 2.37	3.85	Nitrogen
Uwaria	276.17 ± 54.64	140.02 ± 74.43	1.97	Nitrogen
Oele	339.82 ± 34.75	92.94 ± 8.79	3.66	Nitrogen
Ugambe	353.69 ± 26.98	93.01 ± 9.82	3.82	Nitrogen
Utonga	334.12 ± 16.37	85.11 ± 10.51	3.93	Nitrogen
Control	312.14 ± 12.34	83.15 ± 7.32	3.75	Nitrogen

TABLE 5 Mean (±SD) concentrations of total nitrogen (TN) and total phosphorus (TP) at cage and control sites in Kadimu Bay, Lake Victoria, Kenya (TN limitation is considered probable when molar TN:TP ratio is <10 and TP limitation when TN:TP ratio exceeds 20; Maberly et al., 2020).

ranging from light to medium eutrophic are not a threat to aquatic metabolism, but does suggest the possibility of tipping over to eutrophic–hypereutrophic states as the nutrient loading to the lake increases over time. Thus, continuous monitoring of the water quality parameters of the cage sites is needed to sustain aquaculture production and ecosystem functioning (Aura et al., 2020; Masser, 2008). Water quality monitoring is particularly important because the intensity of the eutrophic state varies between months, indicating a potential role of other seasonal drivers such as rainfall and agricultural runoff in affecting water quality of the bay.

4.3 | TN:TP ratios

The TN:TP load for the bay suggests nitrogen limitation since the ratio is <10 (Maberly et al., 2020), similar to recent results observed for other shallow Kenyan lakes such as Lake Baringo (Walumona et al., 2021). Although this finding suggests a likely stronger limitation of nitrogen, compared to TP, in Kenyan freshwater bodies, this suggestion will require more study. Although most freshwater lakes, as well as Lake Victoria (Muggidde et al., 2005), are typically limited by TP, rather than nitrogen (Schindler, 2012; Talling, 1966; Xie et al., 2003), evidence of N limitation has been observed for some freshwater bodies (Elser et al., 1990; Sterner, 2008), prompting debate on the utility of Vollenweider's signal-response TP models to manage lake eutrophication (Sterner, 2008; Vollenweider, 1968). Furthermore, there is argument regarding which of the two nutrients (TP or TN) should be regulated or monitored, with some scientists suggesting only TP control is needed since cyanobacteria will fix N to reduce its limitation (Wurtsbaugh et al., 2019). Control of TP alone, however, has also been questioned (Glibert, 2017; Lewis & Wurtsbaugh, 2008; Paerl et al., 2016), especially for lake basins exhibiting intensive agricultural runoff that may supply TP, thereby making it less limiting. The effects of high TP concentrations in Kadimu Bay, especially at the Uwaria site, and the potential for nutrient co-limitation require further study, noting a more holistic integrated lake basin management approach (ILEC, 2007) may be required to manage the lake environment.

4.4 | Relationship between chlorophyll-a, TP and nitrate concentrations

The relationship between chlorophyll-a, TP and NO_3^- loads for all sites combined indicated a positive linear relationship that was stronger for NO_3^- than for TP, supporting the notion of nitrogen limitation in the lake. It is likely that fish wastes and excess food from the cages, in addition to agricultural loading from the watershed, supply the TP required for phytoplankton growth in the bay, thereby reducing the TP limitation effects (Xie et al., 2003). Nitrogen limitation can be maintained if TP is supplied to the lake in a stochiometric excess of N (including N fixation), and when nitrogen fixation is inhibited by water column nitrate (Sterner, 2008). The exact reasons for the likely nitrogen limitation in the bay, however, require more study. Other studies in the same area indicated the cages exceeded their TP carrying capacity (Sellu Mawundu, unpubl. data), while some studies found TP levels in parts of the lake to be below the eutrophication thresholds (Gikuma-Njuru et al., 2021; Kashindye et al., 2015). Nutrient loading studies of the lake (Chamber et al., 2012; David et al., 2015; Kashindye et al., 2015) have not indicated TP-based eutrophication, due perhaps to high flushing rates or rainfall dilution. Recent studies indicated primary production is nitrogen limited at N:P ratios below 14 and phosphorus limitation at N:P ratios exceeding 16, with co-limitation between the two thresholds (Maberly et al., 2020). The likely lack of TP limitation and the light eutrophic states indicate the TP load to the bay needs to be controlled through large-scale watershed management measures (Schindler, 1971) and control of fish cage feeding activities (Pillay & Kutty, 2005).

5 | CONCLUSIONS

Most of the water quality variables, with the exception of the chlorophyll-a and the DO concentrations and electrical conductivity, were found not to be different between the cage and control sites, indicating a lack of significant influence of the fish cages on water quality variables. The physicochemical variables were within the standard limits for aquatic life processes, implying water quality is not a current challenge from the fish cage culture. Based on the calculated CTSI results, the cage sites in the bay exhibit a light eutrophic state, suggesting eutrophication is not a current threat to fish cage culture. The TP concentrations largely accounted for the CTSI values, with water transparency ranking second. The TN:TP ratio suggested the bay's productivity is nitrogen limited, and that the reason for the apparent TN limitation in the bay will require further studies that include seasonality and which extend to other bays of the lake situated in agricultural watersheds. The apparent prevalence of TN limitation in the bay should inform eutrophication controls measures based on TN and potential TP-TN co-limitation, rather than TP loading alone, as commonly practiced. For sustainable management of cage aquaculture in the lake, it is recommended relevant government agencies should institute monitoring, control and surveillance programmes. The programmes should focus on water quality and nutrient load monitoring, in addition to ensuring good fish farming husbandry. Future studies should also focus on sediment assessments for nutrient loads and interactions between sediments and the water column.

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CONFLICT OF INTEREST STATEMENT

None.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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