Volume 10, Issue No. 01

KENYA Aquatica

A Scientific Journal of Kenya Marine and Fisheries Research Institute

KMFRI

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Editorial

Editorial: Kenya Aquatica Journal Vol 10(1) – *A Showcase of KMFRI's Pioneering Research in Freshwater Ecosystems*

The latest edition of Kenya Aquatica Journal, Vol 10(1) showcases pioneering research by KMFRI scientists on Kenya's freshwater ecosystems. This edition, supported by KMFRI and WIOMSA, covers ecological, socio-economic, and environmental challenges, providing valuable insights into sustainable management practices.

One notable study investigates disease surveillance and antimicrobial resistance in fish from lacustrine caged farms, emphasizing responsible antibiotic use to maintain fish health. Another study explores the impact of organochlorine pesticides on macroinvertebrates in Lake ecosystems, advocating for Rhagovelia spp. as a bioindicator for pesticide monitoring across food webs.

Research on Lake Baringo's small-scale fishery assesses the catch and effort composition, stressing the need for regulatory enforcement to avoid overfishing and advocating for capacity building among stakeholders for sustainable management. Additionally, a study on wild fish kills in Lake Victoria focuses on eutrophication and pollution, recommending integrated watershed management to protect the lake's fisheries and local livelihoods.

A comprehensive study on Lake Elementaita – one of Kanya's flamingos' sanctuaries, combines water quality, fisheries studies, and community surveys, calling for integrated watershed management, conservation, and sustainable agriculture. Research on fisheries co-management in Lake Baringo highlights the importance of local community involvement and sustained achievements in ecosystem management, despite challenges in law enforcement.

An article on the socio-economic dynamics of Lake Victoria proposes establishing a regulatory framework incorporating citizen science to manage the lake's resources for long-term sustainability. Addressing plastic pollution in Lake Turkana, a study recommends waste management solutions, public awareness, and better enforcement of regulations to tackle the issue.

The journal also features research on antimicrobial resistance (AMR), with a review exploring Kenya's aquatic biodiversity for potential novel antimicrobial agents. A genetic research study evaluates freshwater fish populations, identifying gaps and proposing future directions for conservation and management.

Lastly, the journal presents an evaluation of fish market dynamics in Lake Naivasha, recommending infrastructure development like fish markets and hatcheries to support the region's fishery sector.

This edition of Kenya Aquatica Journal provides crucial insights into Kenya's freshwater ecosystems, covering a wide range of research on sustainable management, environmental challenges, and the socio-economic factors influencing aquatic resources. The research highlights KMFRI's ongoing contributions to understanding and addressing these issues, fostering a deeper understanding of Kenya's aquatic biodiversity.

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About Kenya Aquatica

Kenya Aquatica is the Scientific Journal of the Kenya Marine and Fisheries Research Institute (KMFRI). The aim of the Journal is to provide an avenue for KMFRI researchers and partners to disseminate knowledge generated from research conducted in the aquatic environment of Kenya and resources therein and adjacent to it. This is in line with KMFRI's mandate to undertake research in "marine and freshwater fisheries, aquaculture, environmental and ecological studies, and marine research including chemical and physical oceanography", in order to provide sci entific data and information for sustainable development of the Blue Economy.

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Featured front cover picture: Researcher sampling surface plankton in the Kerio River inlet to Lake Turkana. (Photo credit: Mr. John Malala)

Featured back cover picture: Chair of KMFRI Board of Management Amb. Dr. Wenwa Akinyi Odinga Oranga (seated middle), on her right, Ag. KMFRI CEO Dr. James Mwaluma, flanked by KMFRI Heads of Sections: Front (L-R) Dr. Victoria Tarus, Ms Caroline Mukiira, Dr. Jacob Ochiewo, Dr. Irene Githaiga, Mr. Abraham Kagwima. Back (L—R) Mr. Paul Waluba, Ms Jane Kiguta, Dr. Gladys Okemwa, Dr. Eric Okuku, Dr. Joseph Kamau, Mr. Isaac Kojo, Ms Joan Karanja, Mr. Milton Apollo. (Photo credit KMFRI)
Research Vessel MV Mtafiti in the background

Contents

Distribution of organochlorine pesticides in macroinvertebrate functional feeding guild (FFG) of predators, *Rhagovelia spp.* in a tropical estuarine ecosystem

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Abstract

The current world population stands at approximately 8.5 billion people and this number is likely to shoot up in the coming decades. This increaing trend in world population demands the provision of sufficient food, which calls for improved agricultural production systems. In order to achieve this, a tremendous increase in pesticide application of about 30-40% has been documented and this trend is predicted to increase in the coming years. Due to their negative impacts to the environment, some pesticides mainly organochlorine pesticides (OCPs) have since been banned, but their residues can still be detected in different media causing deleterious effects on organisms. The aim of this study, therefore, was to assess the distribution of organochlorine pesticides (OCPs) by aquatic macroinvertebrates FFG of *Rhagovelia* spp. in the tropical estuarine ecosystems of South Coast, Kenya. Twelve sampling stations were purposively identified taking into considerations different hydrological and ecological factors. *Rhagovelia* spp. were sampled using established methods and analysis for OCPs detection were performed using a TSQ Vantage Triple-Stage Quadrupole Mass Spectrophotometer (Thermo Electron) equipped with a heated electrospray ionization probe (HESI-II). Separation, detection, identification and quantification of target analyses followed the same established methods. Sixteen OCPs were recorded in *Rhagovelia* spp. samples collected from all the 12 sampling stations. γ-HCH was the lowest (2.74 0.18 ng g^{-1} dw) recorded concentration value for OCPs from *Rhagovelia* spp. samples whereas OCPs Cis-chlordan, mirex, *p,p'*-DDT, *p,p'*-DDE, *o,p'*-DDE and HCH recorded 10.09 0.35 ng g^{-1} dw, being the highest registered value. Analysis of variance (ANOVA) on the mean concentration residues of OCPs in *Rhagovelia* spp. samples yielded a significant variation among the sampled stations ($F = 77.79$, $df = 11$, $p < 2.2e-16$). The statistical analysis revealed that each station played a crucial role in determining the levels of OCPs in *Rhagovelia* spp. due to environmental factors, early life history strategies of the tested bioassay organism, and different sources of OCPs as influenced by anthropogenic activities. The study recommends for the application of macroinvertebrate FFG of *Rhagovelia* spp. in biomonitoring of estuarian ecosystems. The study also recommends the use of different FFGs of macroinvertebrates such as grazers, collector-gatherers, filterers and shredders in order to bring out the general behavior of these pesticides along the food web.

Keywords: bioaccumulation, estuarine ecosystems, benthic macroinvertebrates, biomonitoring, persistent organic pollutants (POPs), organochlorine pesticides (OCPs)

Introduction

Aquatic environmental degradation by emerging pollutants (EPs) including pesticides is of great interest worldwide. Human pressure has led to the rise of anthropogenic activities, which have contributed to high contamination of aquatic ecosystems by EPs (Zhao *et al.*, 2014). EPs have attracted serious scientific attention in the world that has seen increased research in different environmental partitions such as water, sediments, soil, and organisms (Fair *et al.*, 2018). They are persistent in the aquatic ecosystem thus accumulate in the sediments and enter food webs, posing public health threats to the living biota (Bervoet *et al.*, 2005; Fraysse *et al.*, 2006; Davis *et al.*, 2007; Combi *et al.*, 2016; Montuori *et al.*, 2016, Kayembe *et al.*, 2018; Nyakeya *et al.*, 2022). Further, EPs have the ability to bioconcentrate, bioaccumulate and biomagnify along the food web causing deleterious biological effects. They are major causes of human maladies such as cancer, damage to the nervous system, poor growth rates among newborns due to their toxic, carcinogenic, and mutagenic effects (IARC, 2014).

Pesticides may enter the aquatic environment via anthropogenic activities, mainly agriculture (Nicolau *et al.*, 2006; Reichnberger *et al.*, 2007). It has been argued that owing to their bioavailability in the environment, they have the tendency to be bioconcentrated in organism tissues directly from the water, bioaccumulate and biomagnify within food chains, contaminating higher trophic organisms with higher concentrations of pollutants than their counterparts in lower trophic levels (Hargrave *et al.*, 2000). It is against the aforesaid backdrop, coupled with human health risks upon consumption of sea food that first world countries banned the use of all OCPs in agricultural production (Yuan *et al.*, 2015). In comparison, this is not the case in third world countries, which are struggling with the upsurge in population, hence feeding their people is a challenge (Suami *et al.*, 2020). OCPs are therefore, widely used to boost their agricultural production by preventing pest attacks (Yuan *et al.*, 2015). In addition, DDTs have been reported to be widely used for sanitation purposes in third world countries (UNDP, 2009; Verhaert *et al.*, 2013; Zhang *et al.*, 2013; Kilunga *et al.*, 2017;). OCPs are classified as hydrophobic, take quite a long time to degrade due to their chemical stability, and can easily be adsorbed in the sediments (Montuori *et al.*, 2016). Physicochemical attributes have been shown to affect the concentration and distribution of OCPs in different ecosystems (Poté *et al.*, 2008; Yang *et al.*, 2011; Jiang *et al.*, 2013; Alegria *et al.*, 2016). This, therefore, means that sediments act as sinks for OCPs for an extended period of time (El-Said and Youssef, 2013; Xu *et al.*, 2014), making them to be intimate with functional feeding guilds (FFGs) of macroinvertebrates. It is on this basis that spatial evaluation of OCPs can be of great significance in validating both environmental and ecological risks.

Use of organisms to monitor toxicants in aquatic environment (biomonitoring) has become popular in the recent past (Masese *et al.*, 2013; Nyakeya *et al.*, 2017). Indicator organisms that have been used widely are fish and benthic macroinvertebrates. Such toxicants as pesticides are absorbed by macroinvertebrates at the base of food webs and biomagnified at higher trophic levels (Bard, 1999). Hargrave *et al.* (2000) averred that some macroinvertebrates, depending on the FFGs take up chemicals directly from the water, sediments and/or via predation through bioconcentration. Consequently, they are important prey items for many fish taxa, and create a pathway by which chemical contaminants are bioconcentrated from sediments and bioaccumulated in higher trophic levels (Morrison *et al.*, 1996).

Benthic macroinvertebrates act as the main source of food for fish and other organisms at the top of the food web. They, therefore, provide a clear path of exposure to OCPs and other pollutants for fish and other resident biota along the food web (Nyakeya, *et al.*, 2017). They are thus good bioindicators of aquatic environment because they bioconcentrate pollutants such as pesticides, heavy metals and many more contaminants (Lynch *et al.*, 1988; Hare, 1992; Hare and Campbell, 1992; Nyakeya *et al.*, 2009; Masese *et al.*, 2013; Nyakeya *et al.*, 2017; Nyakeya *et al.*, 2018a, b; Nyakeya *et al.*, 2022).

Other reasons for their preference in screening and biomonitoring of the environment include: their ability to live and be intimate to aquatic sediments and their ability to live for a longer period of time (months to years) which make them accumulate contaminants in their bodies; their ability to live in almost all forms of aquatic systems while found in quite diverse groups; many taxa are fairly sedentary and thus representative of local conditions; many are benthic and thus are closely associated with sediments; they may accumulate pollutants and yet tolerate low moderate contaminant concentrations; toxicant concentrations in the animals appear to be related to those in their environment; a life-span of several months to years allows integration of contaminants into their bodies over a reasonable period of time, but not so long that it avoids short-term changes in the environment; since most are the immature stages of the life-cycle, body concentrations are not affected by reproductive cycles or sexual differences; they are near the base of food chains, so may be vital agents of metal entry into food chains (Masese *et al.*, 2013; Aura *et al.*, 2021; Nyakeya *et al.*, 2022).

Although previous studies have reported on how benthic macroinvertebrates and fish respond to pollution, there exists data paucity on the spatial distribution of pesticides in different FFGs of benthic macroinvertebrates in estuarine ecosystems. Second, although there has been increased interest for research in the bioaccumulation of EPs by aquatic organisms (Vicente-Martorell *et al.*, 2009) since 1970s (Kaushik *et al.*, 2009), there is a gap on the biology of pesticides in estuarine and freshwater organisms (Hare, 1992; Zhou *et al.*, 2008), and their effects (Hare & Campbell, 1992; Gower *et al.*, 1994).

Moreover, in Sub-Saharan Africa (SSA) and particularly in Kenya many of the studies have only reported on either the occurrence of pesticides especially in the inland water bodies (Kiyuka, 2022) but have not related them to macroinvertebrates. In the coastal waters, pesticide studies have dwelt only on distribution, fate and occurrence in sediments (Wandiga *et al.*, 2002; Wandiga *et al.*, 2005; Okuku *et al.*, 2013, 2019, Wanjeri, *et al.*, 2022) and many studies on emerging pollutants have concentrated on heavy metal pollution (Okuku *et al.*, 2010), which also have not shown their ecological effects on organisms. Little studies on the concentration levels of pesticides in fish have been done in Tana and Sabaki Rivers and their respective estuaries (Munga, 1985; Mugachia *et al.*, 1992a, b; Lalah *et al.*, 2003), with little regard to trophic levels. Getting to understand the bioconcentration and biomagnification characteristics of pesticides may not be brought out in order to determine the toxicological risks that are likely to impact on organisms in the environment as well as human health.

Going by the above arguments, it is confirmed that the distribution, occurrence and fate of pesticides has not been studied well to report authoritatively on the state of environment in the region. Furthermore, DDT has not been given the attention it deserves, given that it is one of the most lethal pollutants being reported to be ubiquitous in the environment despite its ban in most of the countries globally and is known to cause deleterious impacts to biota including man (Kiyuka, 2022, Wanjeri *et al.*, 2022). In addition, DDT is in most instances investigated comparatively with other pesticides such as organophosphates which were to replace it in the industrial and agricultural applications because of their less harmful effects and may not persist for long in the environment (Okuku *et al.*, 2019). In such a scenario, very little is known in terms of its impacts to the environment in general. There is need, therefore, for comprehensive studies on the distribution, bioconcentration and biomagnification of OCPs and regular bioassessments and biomonitoring for informed policy development. The present study, therefore, assesses the distribution of OCPs by aquatic macroinvertebrates FFG of *Rhagovelia* spp. in the tropical estuarine ecosystems of South Coast, Kenya. In this regard, the null hypothesis which stated that there is no significant difference in the distribution of OCPs by aquatic macroinvertebrates FFGs of *Rhagovelia* spp. between the sampling stations was tested.

Materials and methods

Study area

The Kenya coast measures about 600 km^2, bordering Somalia to the North at Kiunga (1°41′ S) and Tanzania to the South in a town called Vanga (4°40′ S). The region has a tropical climate whose weather pattern is influenced by of the Western Indian Ocean Monsoon winds. There are two tropical monsoon seasons, the Southeast Monsoon (SEM) prevailing from April to September, which is cooler compared to the Northeast Monsoon (NEM) that is characterized by dry weather and sets from October to March (Nyamora *et al.*, 2018; Nyamora *et al.*, 2023). The wet seasons are experienced between April and October but long rains usually begin towards the end of March with the peak occurring in April or May in case of delays and then start declining through August and September when the dry period beckons. Short rains are then witnessed between October and November.

However, of late, this is no longer the trend as rain of unpredictable heights can be experienced at any time of the year (Nyakeya *et al.*, 2024). Many studies have been concentrated in the North Coast, unlike the South Coast, hence the current study will be undertaken in the Southern region of the Kenyan coast. This region receives the highest mean annual rainfall of slightly above 1,016 mm. It experiences temperature range of between 20°C and 35°C. The study was carried out in 12 sampling stations in the South Coast estuary spread out among 5 sub-estuaries with each delineated with specific sampling sites depending on distinct ecological characteristics: Mapu, Mwena (3 stations), Mkurumudzi (2), Ramisi (3), and Umba (3) estuarine ecosystems in the South Coast of Kenya, within the Western Indian Ocean (WIO) region (Fig. 1).

The area is characterized by one of the largest mangrove habitats (the Vanga-Funzi system covering 6,980 ha). Some of the common mangrove species found in this area include *Rhizophora mucronata* and *Avicenia marina*, plus other seven more species, which support a rich array of biodiversity. Other critical habitats include seagrass meadows and coral reefs. These systems form an important ecological and socio-economic zone for the coastal people. These systems' integrity definitely determines the productivity of the inshore waters and those of the continental shelf areas.

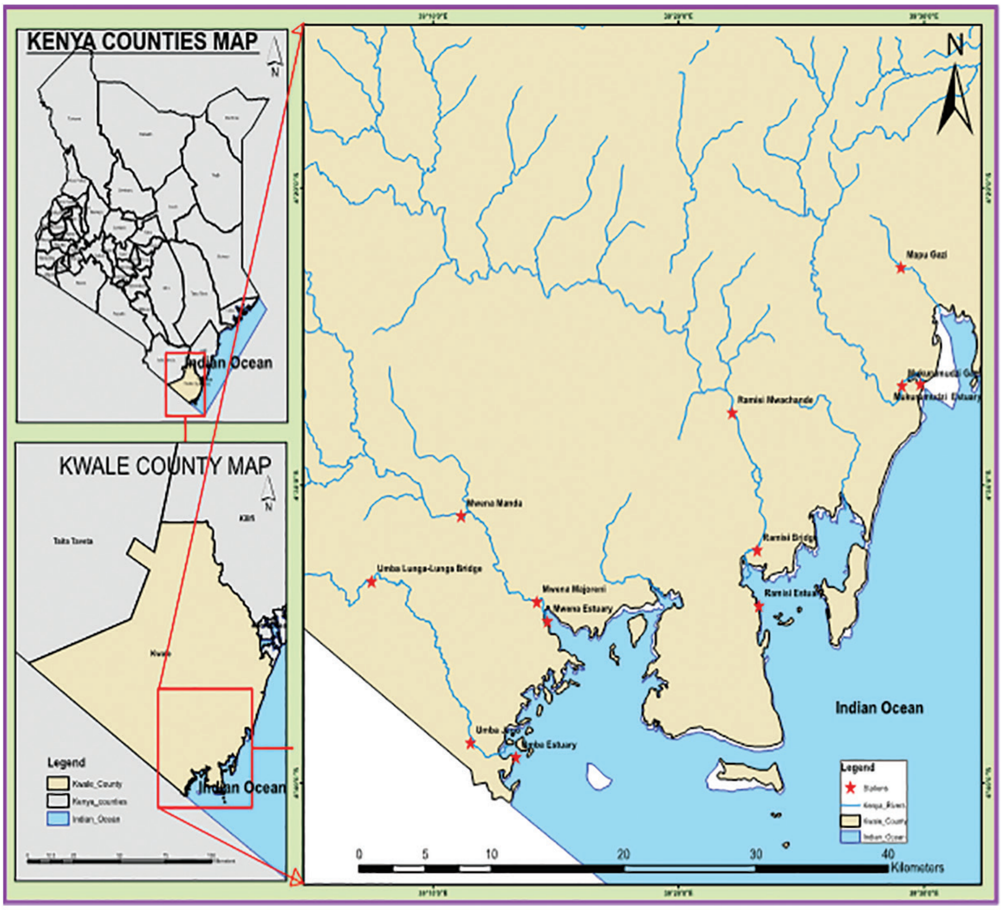

Figure 1. Map of the study area (Source: Authors)**.**

According to the 2019 Census, Kwale County, in which the study area is situated has a total population of 866,820 people, with annual growth pegged at 3.1% (KNBS, 2019). Much of this population (17%) is concentrated along the coastal parts bordering the Indian Ocean, hence impacting the coastal ecosystems and marine habitats via different human induced activities to support their livelihoods. Further, it is projected that this population may increase to 969,442 (i.e., by 10.6%) by the year 2027, meaning much more degradation of both riverine and estuarine systems if sustainable management plans are not put into place (Nyakeya *et al.*, 2024).

The Mkurumudzi River basin, covers an area of 230 km^2 and is located 50 km South of Mombasa City, Kenya. The river traverses about 40 km right from Shimba Hills National Reserve down to Gazi Bay in the Indian Ocean where it supports a vast forest of mangroves in the estuary. It is an important river in the region that support a number of commercial activities such as mining by Base Titanium Limited and irrigation of sugar cane farms mainly run by Kwale International Sugar Company (KISCOL). It also provides water for domestic use and watering of livestock, apart from irrigating small-scale farms in the area (Nyakeya *et al.*, 2024). Of significance also is that it regulates the micro-climate of this semi-arid region. The basin is characterized by a sub-humid climate, and experiences short rains of 800 mm between the months of October and December and long rains between March and May of about 1300 mm.

The river experiences a mean evaporation of 2170 mm year^{-1}, with an aridity index of 0.55 (Katuya, 2014). It is characterizded by warm temperatures during the months of November to April, with mean temperature of 27°C, whereas colder months record an average temperature of 25°C. In the event of low rainfall, the river is recharged by groundwater, making it a permanent river. Agriculture is the major economic activity that takes place whereby crops such as sugarcane, maize, beans, cowpeas, millet and sorghum, okra, cassava) are grown. Livestock husbandry, commercial mining (Base Titanium Ltd., Ukunda, Kenya), commercial farming of sugarcane, commercial mining, tourism activities associated with the sea and the Hills National Reserve, and fishing (in the river and mainly in the Indian Ocean) are other anthropogenic activities of importance.

Ramisi River starts from Chenze Ranges with many first order ephemeral streams feeding it and traverses a mixed terrain before it flows into the Indian Ocean at the Ramisi estuary. It supports an extensive mangrove ecosystem near Funzi Island. The river's salinity characteristics are as a result of in-filtration by brackish geothermal water mainly from Mwananyamala hot springs. Although the underground infiltration makes it somehow saline, it is utilized for irrigation of agricultural crops in the basin. The river supports a mixture of biodiversity including several crocodiles that are distributed along the river continuum depending on the season of the year.

The Umba River on the other hand, is a transboundary river that flows through Tanzania and Kenya. Its source is in the tectonic type of mountain called Usambara in Mkinga, Tanzania, which stands at an altitude of 2,000 m above sea level. This river discharges its waters to the Indian Ocean on the Kenyan part at a small town known as Vanga, near the Kenya-Tanzania border. It traverses a vast area of about 200 km long, carrying with it terrigenous sediments into the estuary. Its total catchment is approximately 8,000 km^2. The river is threatened by numerous anthropogenic activities, but because of its unique biodiversity and the significant ecological role it plays for both countries, a Transboundary Conservation Area (TBCA) extending from Diani, Kwale County in Kenya at an altitude of 39°00′ E, 4°25′ S to Tanga in Tanzania (39°40′ E, 5°10′ S) has been proposed but is yet to be unveiled. The distance between Diani and Mkinga in Tanzania is 120 km. This conservancy shall include a narrow stretch of the coastline in the two countries, covering an estimated area of 2,500 km^2. The TBCA is important because of its contiguous interrelated marine and terrestrial ecosystems with common socio-economic status.

River Mwena traverses about 180 km^2 from its source to the Indian Ocean. It is one of the least studied rivers in the coast of Kenya. It is highly influenced by the anthropogenic activities right from its source because of high population pressure. High water abstraction is prevalent and during the dry seasons its levels reduce drastically. On the other hand, River Mapu acted as the reference point for this study due to its pristine nature owing to the fact that it is surrounded by thick macrophytes and least influenced by anthropogenic activities.

Sampling sites selection and description

The sampling stations were purposively selected taking into considerations different hydrological and ecological factors. Anthropogenic activities along the gradient of each river and urbanization, and at the estuaries where they (rivers) discharge their waters into the ocean were also considered. Therefore, all the sampling sites were located downstream just before the rivers empty their waters into the ocean and immediately after (i.e., at the estuary). Accessibility was also another factor that was taken into account and, therefore, stations before the ocean mainly at designated bridges were given priority. The coordinates of each sampling station were recorded using a handheld Geographical Position System (GPS) device, (Gemina, US). Mapu River was used as the reference point due to the fact that it is minimally impacted. Sampling was done both during the rainy and dry seasons.

Sampling design

A mixed sampling design was employed in this study, whereby both probability and non-probability designs were applied. Purposive sampling design, which is a non-probability design was used to settle on the sampling stations owing to the predetermined (known) factors such as the hydrology, anthropogenic activities along the gradient of each river, urbanization and accessibility and at the estuaries where respective rivers discharge their waters into the ocean. Therefore, the study sites included coastal regions combined with urban and estuarine systems or areas, more so sites impacted by agricultural, urban and freshwater inputs as well as industrial/domestic wastewater effluents. Based on the above criteria, the selected sampling sites were visited purposively in each month for sampling for a period of one year. Probability sampling design i.e., simple random design was then employed to collect *Rhagovelia* spp., the macroinvertebrates FFG of the predator group from pools, runs and rifles.

Sample Collection

Macro-invertebrate sampling and laboratory processing

Rhagovelia spp., which belongs to macroinvertebrate FFG of predators were collected in triplicates at random locations in each of the selected sites with a Surber sampler (0.09 m^2, 250'' mesh size). Samples were preserved in cold corked vials using ethanol (70% v/v) until analyzed in the laboratory. In the field all samples were stored live in cooler boxes, transported to KMFRI Mombasa laboratory in darkness. In the laboratory, samples were immediately transferred into the deep freezer after being sorted and identified up to the lowest levels following macroinvertebrate identification keys for marine (Richmond, 1997; Branch*et al.*, 2008) and freshwater (Gerber and Gabriel, 2002) ecosystems. They were counted, weighed, and frozen at -20°C until analyzed for organochlorine pesticides.

Analysis of pesticides

The detection of OCPs were performed using a TSQ Vantage Triple-Stage Quadrupole Mass Spectrophotometer (Thermo Electron) equipped with a heated electrospray ionization probe (HESI-II). Separation, detection, identification and quantification of target analyses followed methods described by Wille *et al.* (2011). The identification and quantification of OCPs was performed using a 6890N gas chromatograph with an electron capture detector (GC–ECD) (Agilent Technologies) with a 30 m, 0.25 mm i.d. capillary column coated with 5% phenyl-substituted dimethylpolysiloxane phase (0.25 mm film thickness). Automatic split less injections of 2 µL were applied and the total purge rate was adjusted to 50 ml min^{-1}. Hydrogen was used as the carrier gas at a constant pressure of 40 kPa at 100°C, while nitrogen made-up gas at a rate of 60 ml min^{-1}. Injector and detector temperatures were 280°C and 320°C, respectively. Oven temperature was calibrated as follows: 70°C for 1 minute, raised at 40°C min^{-1} to 170°C, then raised at 1.5°C min^{-1} to 230°C for 1 minute and at 30°C min^{-1} to 300°C with a final hold of 5 minutes.

Quality assurance and quality control

Quality assurance/quality control (QA/QC) of the analytical methods was ensured by the use of a standard reference material (SRM 1941b – organics in marine sediment) purchased from the National Institute of Standards and Technology (USA). This was done in duplicate and the average recovery of analytes was obtained. The analytes recovery was achieved through spiked blanks and matrices. Analytes in procedural blanks were subtracted from the samples. Laboratory check solutions were routinely injected into GC–ECD and GC–MS to confirm instrument accuracy and precision. Calibration of the instruments was performed using a nine-level analytical curve. Quantification of analytes followed the internal standard procedure and the surrogate recoveries were acceptable.

Statistical Analysis

Data were presented as means (±SD) after testing for normality and homogeneity of variances, using Levene's and Shapiro-Wilk tests (Levene, 1960; Lina *et al.*, 2015). Analysis of variance (ANOVA) was used to test for significant differences among sampling stations. Tukey's post-hoc multiple comparison test was applied to determine which sites differed significantly from one other. All the analysis was done using the 64-bit R Software version 4.3.0 (R-core team, 2023). All the observed differences were considered statistically significant at $p < 0.05$.

Results

Figure 2 depicts the mean concentration values of a) heptachlor, b) H-hepoxide, c) Cis-chlordane d) T-nonachlor, e) HCB and f) mirex pesticides in macroinvertebrate FFGs for *Rhagovelia* spp. sampled in the South Coast estuarine ecosystems of Kenya. Heptachlor pesticides in *Rhagovelia* spp. registered a mean concentration value of 5.54 ± 2.04 ng g^{-1} dw in the twelve sampled stations; while the lowest (2.87 ± 0.15 ng g^{-1} dw) value was observed at station RB and the highest (9.03 ± 0.33 ng g^{-1} dw) at ME. Analysis of variance (ANOVA) for the mean concentration of heptachlor pesticides in *Rhagovelia* spp. sampled among the twelve sites demonstrated that they differed significantly ($F = 157.16$, df = 11, $p \leq 2.2e-16$). In addition, post-hoc Tukey's test inferred a significant difference in the mean concentration of heptachlor pesticides for *Rhagovelia* spp. among stations ME (9.03 ± 0.33 ng g^{-1} dw), MG (3.77 ± 0.25 ng g^{-1} dw), MKE (4.12 ± 0.31 ng g^{-1} dw), MM (6.89 ± 0.18 ng g^{-1} dw), MAPU (6.34 ± 0.25 ng g^{-1} dw), RB (2.84 ± 0.15 ng g^{-1} dw), RE (4.38 ± 0.29 ng g^{-1} dw), and UL (5.21 ± 0.45 ng g^{-1} dw). Conversely, stations ME and MMJ; MG and RM; MM and UE; and RE and ULB did not show any significant differences in the mean concentrations of heptachlor pesticides for *Rhagovelia* spp. at $p < 0.05$.

Additionally, H-hepoxide pesticides mean concentration levels in *Rhagovelia* spp. samples sampled along the sampling stations during the study period ranged from 3.92 ± 0.26 to 10.09 ± 0.35 ng g^{-1} dw for stations ME and UE respectively with a mean concentration of 7.04 ± 1.82 ng g^{-1} dw (Fig. 2b). The mean concentration values in H-hepoxide for *Rhagovelia* spp. samples were significantly different among the twelve sampled stations ($F = 106.71$, df = 11, $p = 2.2e-16$). When the means were subjected to post-hoc Tukey's test, it revealed that many of the stations were statistically different from one another (i.e., ME, 3.92 ± 0.26 ng g^{-1} dw; MG, 7.65 ± 0.28 ng g^{-1} dw; MKE, 7.44 ± 0.21 ng g^{-1} dw; MM, 6.37 ± 0.25 ng g^{-1} dw; MMJ, 8.23 ± 0.40 ng g^{-1} dw; MAPU, 4.92 ± 0.34 ng g^{-1} dw; RM, 5.94 ± 0.40 ng g^{-1} dw; UE, 10.09 ± 0.35 ng g^{-1} dw; and UL, 9.06 ± 0.32 ng g^{-1} dw). Stations MKE and RE; MMJ and ULB; and MAPU and RB on the other hand did not differ statistically.

Cis-chlordane concentration in *Rhagovelia* spp. ranged from 5.94 ± 0.40 to 10.09 ± 0.35 ng g^{-1} dw with a mean of 7.71 ± 1.2 ng g^{-1} dw (Fig. 2c). Sampling station RE recorded the highest concentration (10.09 ± 0.35 ng g^{-1} dw) whereas MAPU had the least (5.94 ± 0.40 ng g^{-1} dw). A significant difference between the sampling stations was observed ($F = 27.83$; df = 11; $p \leq 2.2e-16$). A post-hoc Tukey's test on the other hand, showed that stations ME (8.09 ± 0.33 ng g^{-1} dw), MG (6.69 ± 0.22 ng g^{-1} dw), MKE (8.64 ± 0.34 ng g^{-1} dw), MM (6.73 ± 0.25 ng g^{-1} dw), MMJ (7.41 ± 0.18 ng g^{-1} dw), MAPU (5.94 ± 0.40 ng g^{-1} dw) and RE (10.09 ± 0.35 ng g^{-1} dw) differed significantly at $p < 0.05$. Stations ME, RB and ULB; MG and UL; MKE and UE; and MMJ and RM were not significantly different.

The mean concentration level of HCB in *Rhagovelia* spp. samples was 7.08 ± 1.92 ng g^{-1} dw with station UL recording the highest value of 10.09 ± 0.35 ng g^{-1} dw while MAPU station recorded the lowest (3.16 ± 0.42 ng g^{-1} dw) (Fig. 2d). Analysis of variance (ANOVA) on the mean concentration residues of HCB pesticides in *Rhagovelia* spp. samples yielded a significant variation among the sampled stations ($F = 77.79$, df = 11, $p \leq 2.2e-16$). Tukey's HSD pairwise mean comparisons on the concentration values of HCB pesticides in *Rhagovelia* spp. showed a significant difference in stations ME (9.03 ± 0.33 ng g^{-1} dw), MG (5.21 ± 0.45 ng g^{-1} dw), MKE (7.23 ± 0.30 ng g^{-1} dw), MM (6.69 ± 0.22 ng g^{-1} dw), MMJ (8.64 ± 0.34 ng g^{-1} dw), MAPU (3.16 ± 0.42 ng g^{-1} dw), RB (5.94 ± 0.40 ng g^{-1} dw), UE (8.09 ± 0.32 ng g^{-1} dw) and UL (10.09 ± 0.35 ng g^{-1} dw). In contrast, such stations as MG (5.21 ± 0.45 ng g^{-1} dw) and RM (5.44 ± 0.41 ng g^{-1} dw); MKE (7.23 ± 0.30 ng g^{-1} dw) and RE (7.41 ± 0.18 ng g^{-1} dw); and UE (8.09 ± 0.32 ng g^{-1} dw) and ULB (8.09 ± 0.33 ng g^{-1} dw) were statistically not different at $p < 0.05$.

Mirex was yet another pesticide that was found in the *Rhagovelia* spp. during the study period in the South Coast estuarine ecosystems of Kenya (Fig. 2f). Its concentration level in all the sampled stations ranged between 3.03 ± 0.13 ng g^{-1} dw at MMJ station and 10.09 ± 0.35 ng g^{-1} dw at RE station; and a mean value of 7.26 ± 1.94 ng g^{-1} dw. There was no significant difference that was registered in the concentration levels of mirex pesticides in *Rhagovelia* spp. sampled in the twelve sampling stations ($F = 102.37$, df = 11, $p = 2.2e-16$). Furthermore, Tukey's HSD pairwise mean comparisons test revealed that there existed significant differences in the means of mirex concentrations of *Rhagovelia* spp. in such stations as ME (4.38 ± 0.29 ng g^{-1} dw); MG (8.09 ± 0.33 ng g^{-1} dw); MKE (9.08 ± 0.33 ng g^{-1} dw); MM (7.45 ± 0.19 ng g^{-1} dw); MMJ (3.03 ± 0.13 ng g^{-1} dw); RE (10.09 ± 0.35 ng g^{-1} dw); RM (7.30 ± 0.33 ng g^{-1} dw); UE (6.73 ± 0.25 ng g^{-1} dw) and UL (8.64 ± 0.34 ng g^{-1} dw) at $p < 0.05$. On the contrary, stations MG (8.09 ± 0.33 ng g^{-1} dw) and RB (8.09 ± 0.33 ng g^{-1} dw); MM (7.45 ± 0.19 ng g-1 dw) and MAPU (7.44 ± 0.21 ng g^{-1} dw); and UE (6.73 ± 0.25 ng g^{-1} dw) and ULB (6.75 ± 0.22 ng g^{-1} dw) did not differ significantly.

p,p'-DDE, *o,p'*-DDE, *o,p'*-DDD, *p,p'*-DDD, *o,p'*-DDT and *p,p'*-DDT concentration levels in macroinvertebrate FFGs for *Rhagovelia* spp. are shown below (Fig. 3). *p,p'*-DDE concentrations in *Rhagovelia* spp. among the twelve stations were also measured. The lowest mean of 3.92 ± 0.26 ng g^{-1} dw was observed in station RE and the highest (10.09 ± 0.35 ng g^{-1} dw) in station MM (Fig. 3a). A mean concentration of 7.20 ± 1.55 ng g^{-1} dw was recorded. There was a significant difference in the mean concentration of *p,p'*-DDE pesticides in *Rhagovelia* spp. sampled in the twelve stations ($F = 66.17$, df = 11, $p \leq 2.2e-16$). Further, post-hoc Tukey's HSD pairwise mean comparisons displayed a significant difference in the mean concentration of *p,p'*-DDE pesticides in *Rhagovelia* spp. among stations ME (6.64 ± 0.23 ng g^{-1} dw), MKE (7.41 ± 0.18 ng g^{-1} dw), MM (10.09 ± 0.35 ng g^{-1} dw), MMJ (8.09 ± 0.32 ng g^{-1} dw), and RE (3.92 ± 0.26 ng g^{-1} dw). There was no statistical difference among stations ME (6.64 ± 0.23 ng g^{-1} dw), MG (6.21 ± 0.33 ng g^{-1} dw), RM (6.22 ± 0.27 ng g^{-1} dw) and ULB (6.02 ± 0.37 ng g^{-1} dw); MKE (7.41 ± 0.18 ng g^{-1} dw) and UL (7.41 ± 0.18 ng g^{-1} dw); and MMJ (8.09 ± 0.32 ng g^{-1} dw), MAPU (8.09 ± 0.32 ng g^{-1} dw), RB (8.23 ± 0.40 ng g^{-1} dw), and UE (8.09 ± 0.33 ng g^{-1} dw).

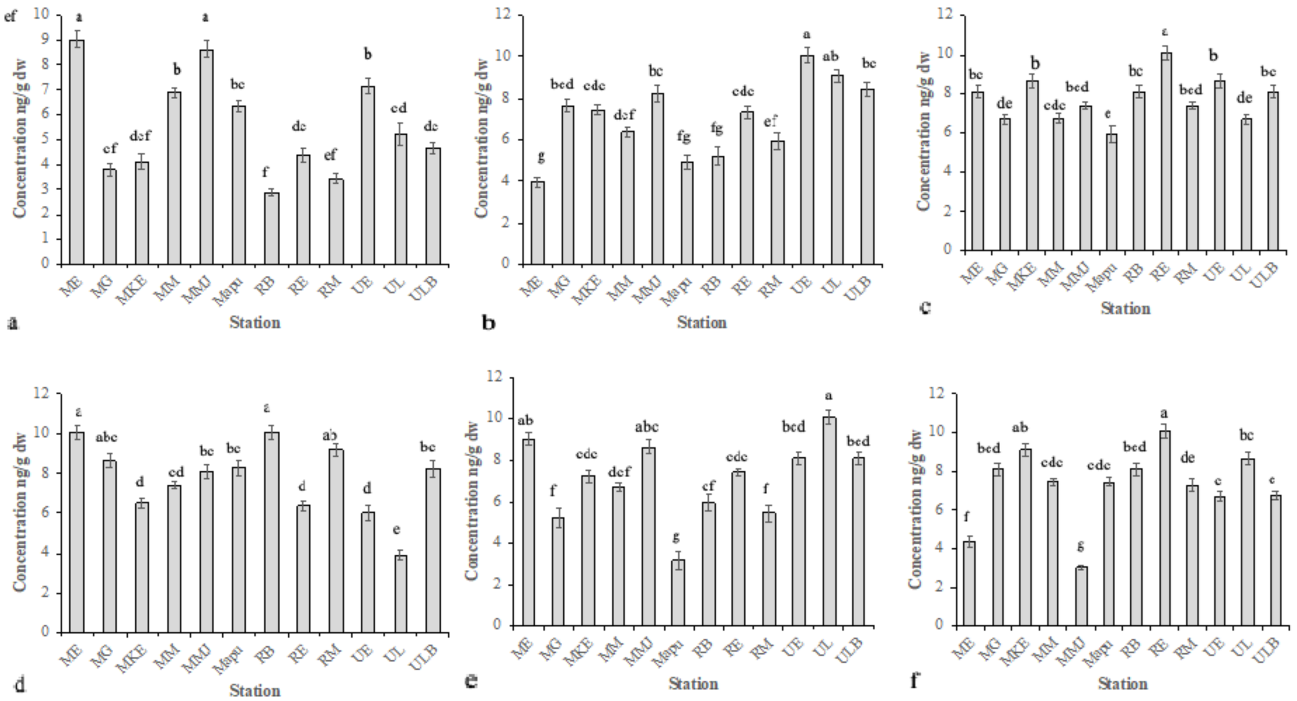

Figure 2. Spatial mean (± SD) concentrations in a) heptachlor, b) H-hepoxide, c) Cis-chlordane d) T-nonachlor, e) HCB and f) mirex pesticides in *Rhagovelia* spp. (predator) sampled in the twelve stations at the South Coast estuarine systems of Kenya. Superscript letters represent mean differences among the sampling stations obtained by performing Tukey HSD pairwise mean comparisons. ME: Mwena Estuary; MG: Mkurumudzi Gazi; MKE: mkurumudzi Estuary; MM: Mwena Manda; MMJ: Mwena Majoreini; RB: Ramisi Bridge; RE: Ramisi Estuary; RM: Ramisi Mwachande; UE: Umba Estuary; UL: Umba Lenjo; ULB: Umba Lunga-lunga Bridge.

For *o,p'*-DDE pesticides in macroinvertebrate for *Rhagovelia* spp. sampled in the South Coast estuarine ecosystems of Kenya, its mean concentration ranged between 5.12 ± 0.46 ng g^{-1} dw, station ULB and 10.09 ± 0.35 ng g^{-1} dw, station MKE; and its overall mean was 7.15 ± 1.64 ng g^{-1} dw (Fig. 3b). There existed a significant difference in the mean concentration of *o,p'*-DDE pesticides in macroinvertebrate for *Rhagovelia* spp. among the sampled stations (F = 67.46, df = 11, p ≤ 2.2e-16). A post-hoc Tukey's test further confirmed significant differences between different mean in *o,p'*-DDE pesticides in macroinvertebrates for *Rhagovelia* spp. for the following stations: ME (8.64 ± 0.34 ng g^{-1} dw), MG (8.09 ± 0.33 ng g^{-1} dw), MKE (10.09 ± 0.35 ng g^{-1} dw), MMJ (6.95 ± 0.17 ng g^{-1} dw), and MAPU (4.41 ± 0.28 ng g^{-1} dw). There was no significant difference, however, reported on stations: ME (8.64 ± 0.34 ng g^{-1} dw) and MM (8.64 ± 0.34 ng g^{-1} dw); MG (8.09 ± 0.33 ng g^{-1} dw), RB (7.15 ± 0.30 ng g^{-1} dw), RE (7.44 ± 0.21 ng g^{-1} dw), and UL (7.15 ± 0.30 ng g^{-1} dw); MMJ (6.95 ± 0.17 ng g^{-1} dw) and UE (6.89 ± 0.18 ng g^{-1} dw); and MAPU (4.41 ± 0.28 ng g^{-1} dw), RM (5.21 ± 0.45 ng g^{-1} dw) and ULB (5.12 ± 0.46 ng g^{-1} dw).

The highest concentration of *o,p'*DDD pesticides in *Rhagovelia* spp. was observed at station ME, 9.03 ± 0.33 ng g^{-1} dw while the lowest mean was recorded at station MG (2.85 ± 0.16 ng g^{-1} dw) (Fig. 3c). The mean concentration value for all the sampled stations was 5.98 ± 0.28 ng g^{-1} dw. The concentrations of *o,p'*-DDD levels in *Rhagovelia* spp. were significantly different in all the stations (F = 199.19, df = 11, p ≤ 2.2e-16). To test whether each of the station means were statistically different, post-hoc Tukey's test revealed that the concentrations of *o,p'*-DDD in *Rhagovelia* spp. at stations ME, MG, MKE, RB, and UE differed significantly at p < 0.05. Stations ME, MM and MMJ; MG, MAPU and RM; RB, RE and ULB; and UE and UL on the other hand were statistically similar.

The residues of *p,p'*-DDD concentration in *Rhagovelia* spp. varied from 3.92 ± 0.26 to 9.03 ± 0.33 ng g^{-1} dw for stations MG and MAPU respectively (Fig. 3d). The average concentration of *p,p'*-DDD for *Rhagovelia* spp. sampled in the twelve stations was 6.46 ± 1.63 ng g^{-1} dw. The concentration of *p,p'*-DDD in *Rhagovelia* spp. differed significantly (F = 73.61, df = 11, p ≤ 2.2e-16) among the twelve sampled stations. A post-hoc Tukey's test analysis displayed a significant difference in the different mean concentrations of *p,p'*-DDD in *Rhagovelia* spp. sampled at stations MAPU (9.03 ± 0.33 ng g^{-1} dw), UE (8.55 ± 0.35 ng g^{-1} dw), and UL (6.67 ± 0.22 ng g^{-1} dw) at $p < 0.05$. The rest of the remaining stations did not differ statistically (i.e., ME (4.81 ± 0.28 ng g^{-1} dw), MG (3.92 ± 0.26 ng g^{-1} dw), MKE (5.13 ± 0.46 ng g^{-1} dw), RB (4.80 ± 0.21 ng g^{-1} dw) and RE (5.21 ± 0.45 ng g^{-1} dw); MM (7.51 ± 0.26 ng g^{-1} dw), MMJ (7.44 ± 0.21 ng g^{-1} dw), RM (7.18 ± 0.29 ng g^{-1} dw) and ULB (7.23 ± 0.30 ng g^{-1} dw).

Station MM recorded the highest mean concentration value (9.03 ± 0.33 ng g^{-1} dw) for *o,p'*-DDT pesticide in *Rhagovelia* spp. while MG had the lowest (3.38 ± 0.38 ng g^{-1} dw); the mean concentration value was 6.84 ± 1.62 ng g^{-1} dw (Fig. 3e). ANOVA revealed that the mean concentration values for *o,p'*-DDT pesticide in *Rhagovelia* spp. differed statistically across stations (F = 86.93, df = 11, p ≤ 2.2e-16). Tukey's HSD pairwise mean comparisons for *o,p'*-DDT pesticide in *Rhagovelia* spp. across different stations revealed that there was significant differences between stations ME (8.55 ± 0.35 ng g^{-1} dw), MG (3.38 ± 0.38 ng g^{-1} dw), MKE (5.44 ± 0.41 ng g^{-1} dw), MM (9.03 ± 0.33 ng g^{-1} dw), MMJ (6.71 ± 0.21 ng g^{-1} dw), MAPU (7.15 ± 0.30 ng g^{-1} dw) and RM (7.44 ± 0.21 ng g^{-1} dw). Alternatively, stations MKE (5.44 ± 0.41 ng g^{-1} dw), RB (5.67 ± 0.36 ng g^{-1} dw) and UL (5.51 ± 0.34 ng g^{-1} dw); MAPU (7.15 ± 0.30 ng g^{-1} dw) and RE; and RM (7.44 ± 0.21 ng g^{-1} dw) and ULB (7.44 ± 0.21 ng g^{-1} dw) were statistically not different at $p < 0.05$.

The highest concentration of *p,p'*-DDT pesticides in *Rhagovelia* spp. sampled in the South Coast of Kenya among the twelve stations occurred at station RE (10.09 ± 0.35 ng g^{-1} dw), whereas the lowest was recorded at MAPU (5.94 ± 0.40 ng g^{-1} dw) with a mean of 7.75 ± 1.11 ng g^{-1} dw) (Fig. 3f). There was significant difference (F = 27.36, df = 11, p ≤ 2.2e-16) in the mean concentration of *p,p'*-DDT pesticides in *Rhagovelia* spp. among the sampling stations. In addition, Tukey HSD pairwise mean comparisons for *p,p'*-DDT pesticides in *Rhagovelia* spp. revealed significant differences among stations ME (7.41 ± 0.18 ng g^{-1} dw), MKE (7.07 ± 0.31 ng g^{-1} dw), MM (8.64 ± 0.34 ng g^{-1} dw), MAPU (5.94 ± 0.40 ng g^{-1} dw), RE (10.09 ± 0.35 ng g^{-1} dw) and ULB (8.71 ± 0.38 ng g^{-1} dw). In contrast, stations ME (7.41 ± 0.18 ng g^{-1} dw), MG (8.09 ± 0.32 ng g^{-1} dw), RB (8.09 ± 0.33 ng g^{-1} dw), RM (7.41 ± 0.18 ng g^{-1} dw) and UL (8.09 ± 0.32 ng g^{-1} dw); and MKE (7.07 ± 0.31 ng g^{-1} dw), MMJ (6.73 ± 0.25 ng g^{-1} dw) and UE (6.69 ± 0.22 ng g^{-1} dw).

The mean concentration of HCN, α-HCH, γ-HCH and ß-HCH pesticides in macroinvertebrate FFGs for *Rhagovelia* spp. as recorded in different stations is illustrated in Figure 4. The mean concentration of HCN pesticide in the *Rhagovelia* spp. sampled along different sampling stations in South Coast estuarine systems of Kenya was 7.57 ± 1.71 ng g^{-1} dw; and ranged from 3.32 ± 0.19 to 10.09 ± 0.35 ng g^{-1} dw (Fig. 4a). There existed significant statistical differences (F = 96.39, df = 11, p ≤ 2.2e-16) in the mean concentration of HCN pesticide for *Rhagovelia* spp. samples across the sampling stations. Post-hoc Tukey's test showed a significant difference among the means of concentration levels in HCN pesticides for *Rhagovelia* spp. (ME, 3.32 ± 0.19 ng g^{-1} dw; MG, 7.26 ± 0.22 ng g^{-1} dw; MKE, 8.09 ± 0.33 ng g^{-1} dw; MMJ, 9.03 ± 0.33 ng g^{-1} dw; MAPU, 5.99 ± 0.35 ng g^{-1} dw; RB, 7.43 ± 0.30 ng g^{-1} dw; RM, 8.07 ± 0.27 ng g^{-1} dw; UE, 6.69 ± 0.22 ng/g and ULB, 10.09 ± 0.35 ng g^{-1} dw). However, there was no statistical difference in the mean concentrations of HCN pesticides for *Rhagovelia* spp. among stations MKE (8.09 ± 0.33 ng g^{-1} dw), MM (8.64 ± 0.34 ng g^{-1} dw), RE (8.09 ± 0.33 ng g^{-1} dw) and UL (8.09 ± 0.32 ng g^{-1} dw).

The concentration values for α-HCH pesticides in *Rhagovelia* spp. among the sampling stations was 6.7 ± 1.9 ng g^{-1} dw with the values ranging

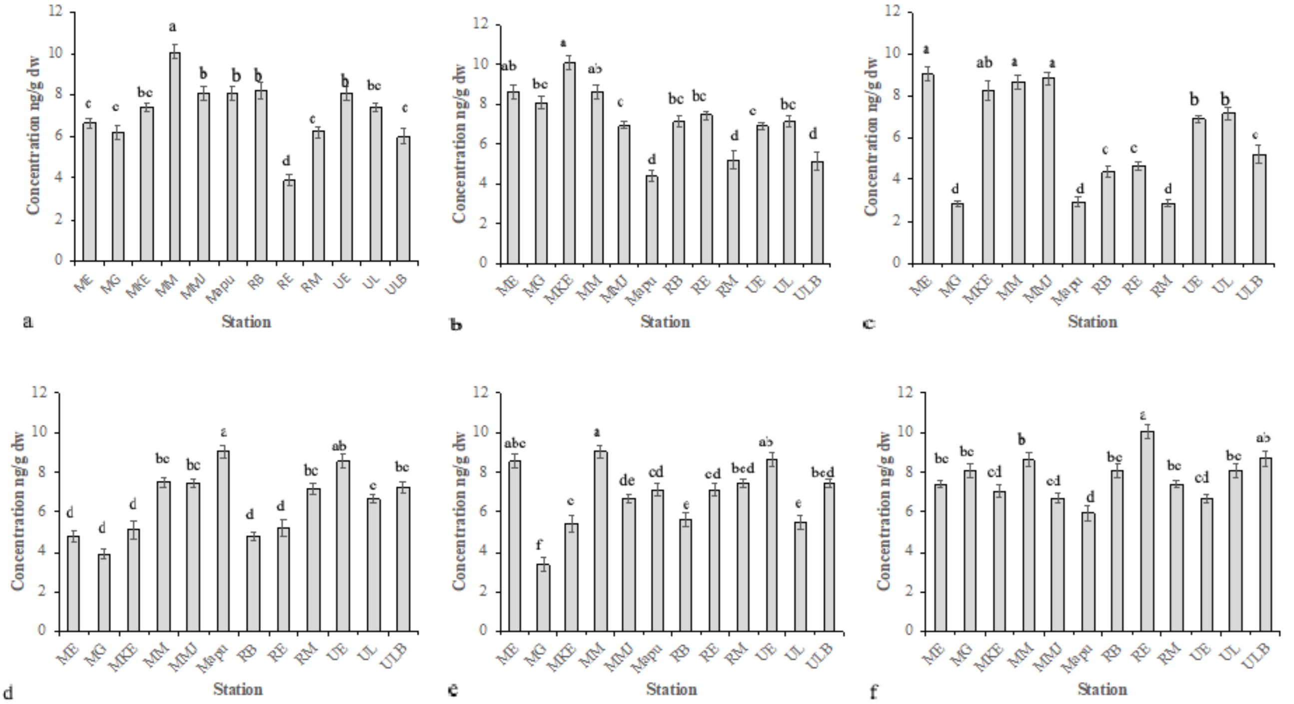

Figure 3. Mean (±SD) spatial variation in the concentration of a) *p,p'*-DDE, b) *o,p'*-DDE, c) *o,p'*-DDD d) *p,p'*-DDD, e) *o,p'*-DDT and f) *p,p'*-DDT pesticides in macroinvertebrate FFGs for *Rhagovelia* spp. in estuarine systems of South Coast, Kenya. The superscript letters represent mean differences among the stations obtained by performing Tukey's pairwise mean comparisons. ME: Mwena Estuary; MG: Mkurumudzi Gazi; MKE: mkurumudzi Estuary; MM: Mwena Manda; MMJ: Mwena Majoreini; RB: Ramisi Bridge; RE: Ramisi Estuary; RM: Ramisi Mwachande; UE: Umba Estuary; UL: Umba Lenjo; ULB: Umba Lunga-lunga Bridge.

between 3.32 ± 0.19 ng g^{-1} dw and 9.08 ± 0.33 ng g^{-1} dw (Fig. 4b). There was a significant difference in mean concentration levels of α-HCH pesticides for *Rhagovelia* spp. among the sampling stations at $p < 0.05$ level for the twelve stations ($F = 34.32$, df = 11, $p \leq 2.2e-16$). Post-hoc Tukey's test results revealed that stations ME (9.08 ± 0.33 ng g^{-1} dw), MG (5.05 ± 0.44 ng g^{-1} dw), MKE (7.20 ± 0.30 ng g^{-1} dw), MM (6.67 ± 0.22 dg g^{-1} dw), MMJ (8.55 ± 0.35 ng g^{-1} dw), MAPU (6.42 ± 0.29 ng g^{-1} dw), RE (3.32 ± 0.19 ng g^{-1} dw), UL (5.21 ± 0.45 ng g^{-1} dw) and ULB (4.38 ± 0.29 ng g^{-1} dw) differed significantly with station ME recording the highest mean concentration (9.08 ± 0.33 ng g^{-1} dw) and RE the least (3.32 ± 0.19 ng g^{-1} dw). Stations ME and RB; MKE and UE; MMJ and RM did not differ statistically (ME = RB; MKE = UE; and MMJ = RM).

Gamma-HCH concentrations in *Rhagovelia* spp. among the sampling stations registered a mean of 6.7 ± 2.22 ng g^{-1} dw with values ranging from 2.74 ± 0.18 ng g^{-1} dw, MAPU station to 9.45 ± 0.51 ng g^{-1} dw at station MMJ (Fig. 4c). The mean concentration residues of γ-HCH pesticides in *Rhagovelia* spp. differed significantly among the sampling stations ($F = 120.90$, df = 11, $p \leq 2.2e-16$). Multiple pairwise comparison Tukey's test indicated that stations ME (4.18 ± 0.27 ng g^{-1} dw), MG (9.03 ± 0.33 ng g^{-1} dw), MKE (7.18 ± 0.29 ng g^{-1} dw), MAPU (2.74 ± 0.18 ng g^{-1} dw), RB (5.21 ± 0.45 ng g^{-1} dw) and UE (8.64 ± 0.34 ng g^{-1} dw) were statistically different at $p < 0.05$. On the other hand, stations MG (9.03 ± 0.33 ng g^{-1} dw), MM (9.03 ± 0.33 ng g^{-1} dw), MMJ (9.45 ± 0.51 ng g^{-1} dw); MKE (7.18 ± 0.29 ng g^{-1} dw), RE (7.15 ± 0.30 ng g^{-1} dw), ULB (7.44 ± 0.21 ng g^{-1} dw); and RB (5.21 ± 0.45 ng g^{-1} dw), RM (4.38 ± 0.29 ng g^{-1} dw) and UL (5.51 ± 0.34 ng g^{-1} dw) were statistically not significant.

The mean concentration of ß-HCH pesticides in *Rhagovelia* spp. on the other hand ranged from 3.32 ± 0.19 ng g^{-1} dw (station UL) to 9.28 ± 0.55 ng g^{-1} dw at MAPU station with a mean of 6.8 ± 2.08 ng g^{-1} dw (Fig. 4d). There was a significant difference observed in the mean concentration residues of ß-HCH pesticides in *Rhagovelia* spp. among the sampling stations (F = 147.48, df = 11, p ≤ 2.2e-16). Post-hoc comparisons using Tukey HSD test on the mean concentration values of ß-HCH pesticides in *Rhagovelia* spp. denoted that stations ME (7.44 ± 0.21 ng g^{-1} dw), MG (8.23 ± 0.40 ng g^{-1} dw), MKE (3.92 ± 0.26 ng g^{-1} dw), MM (5.21 ± 0.45 ng g^{-1} dw), MAPU (9.28 ± 0.55 ng g^{-1} dw), RB (6.69 ± 0.22 ng g^{-1} dw), RE (8.64 ± 0.34 ng g^{-1} dw) and UL (3.32 ± 0.19 ng g^{-1} dw) were different statistically (p < 0.05). Conversely, stations ME (7.44 ± 0.21 ng g^{-1} dw) and MMJ (7.15 ± 0.30 ng g^{-1} dw); MG (8.23 ± 0.40 ng g^{-1} dw) and RM (8.09 ± 0.32 ng g^{-1} dw); MKE (3.92 ± 0.26 ng g^{-1} dw) and UE (4.38 ± 0.29 ng g^{-1} dw) were statistically similar..

Discussion

The analysis conducted on the macroinvertebrates FFG of *Rhagovelia* spp. data revealed significant temporal effects on various OCPs levels. The low p-values (p < 2.2e-16) associated with each factor indicated a high degree of statistical significance, providing strong evidence against the null hypothesis of "no significant effect" of stations on OCPs concentrations. Further significant differences noted by different OCPs concentrations from *Rhagovelia* spp. samples among the sampling stations could be explained by the localized sources of pesticides or environmental conditions. Some of the associated sources of OCPs concentrations could vary from agricultural practices to urbanization and probably due to industrial effluents. This could occur through surface run-off and sub-surface infiltration into estuarine systems. Equally, the temporal distribution was attributed to climatic factors and the seasonal anthropogenic occurrences related to crop pest control and management.

Therefore, the bioassay of benthic macroinvertebrates' body concentrations of OCPs can be utilized to explain the state of environmental perturbation because they play a key role in measuring the bioavailability of a given contaminant in the environment (Solà & Prat, 2006; Peter, *et al.*, 2018). The *Rhagovelia* spp. showed

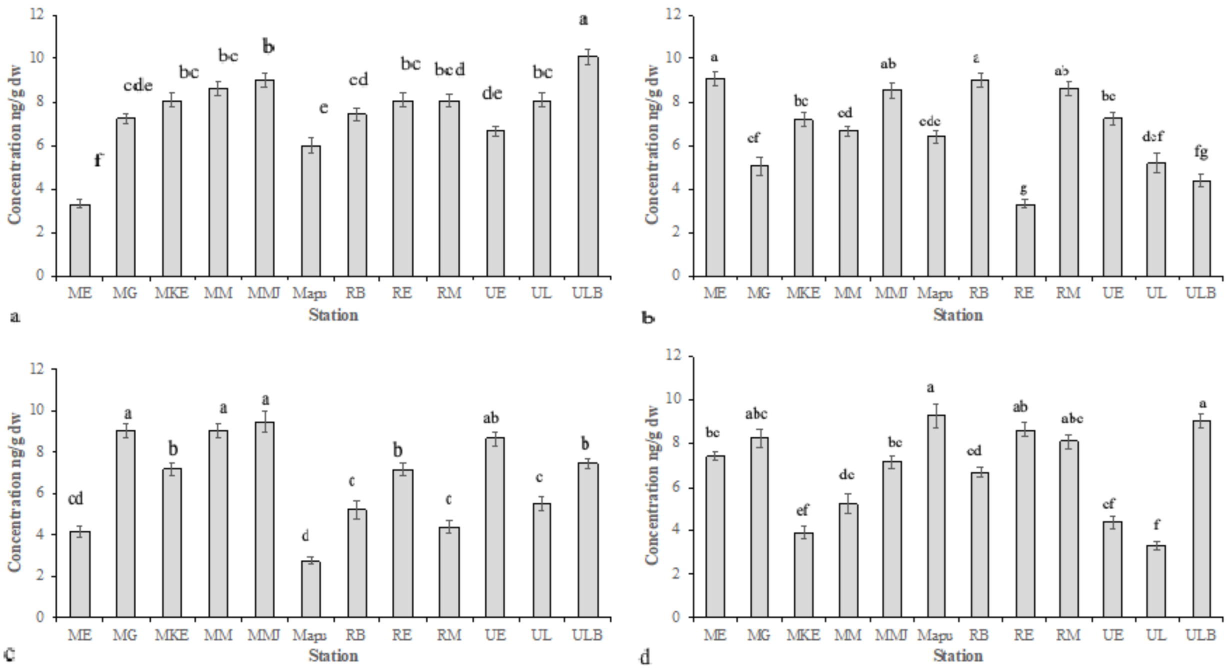

Figure 4. Mean (±SD) spatial variation in the concentration of a) HCN, b) α-HCH, c) γ-HCH and d) ß-HCH pesticides in macroinvertebrate FFGs for *Rhagovelia* spp. in estuarine systems of South Coast, Kenya. The superscript letters represent mean differences among the sampling stations obtained by performing Tukey's pairwise mean comparisons. ME: Mwena Estuary; MG: Mkurumudzi Gazi; MKE: mkurumudzi Estuary; MM: Mwena Manda; MMJ: Mwena Majoreini; RB: Ramisi Bridge; RE: Ramisi Estuary; RM: Ramisi Mwachande; UE: Umba Estuary; UL: Umba Lenjo; ULB: Umba Lunga-lunga Bridge.

that irrespective of the varying conditions of different sampling sites, it could easily bioconcentrate the OCPs although in different concentration levels hence a recommendable candidate for toxicological studies. Even though this study utilized the entire body of the organism owing to laborious work involved in separating different body tissues due to the bioassay organism's body size, internal composition and distribution of contaminants among body organs/tissues is not homogeneous because the distribution patterns is both pollutant and species-specific or broadly, taxon-specific (Hare *et al.*, 2003). This study, therefore, corroborated well with Hare (1992) who averred that FFGs of macroinvertebrates readily bind OCPs contaminants on the surface of their exoskeleton and body organs, hence detecting them in the entire body (Franzle, 2015). This is the strategy the present study adopted whereby the entire body of the macroinvertebrate FFG of the *Rhagovelia* spp. was utilized thus offering the best environmental solution (Pastorino *et al.*, 2020a) as far as the OCPs contamination is concerned because they were bioavailable in all sampling sites.

The spatial patterns displayed by the OCPs could have been induced by a number of physicochemical water quality attributes or the environmental factors. The bioavailability of a given contaminant such as that of pesticides can be influenced by such parameters as the water pH, conductivity, temperature, TDS, redox potential, salinity and total organic content, and is the percentage of the total sum of pesticides that is available in time and space for adsorption by an organism (Tessier & Turner, 1995; Peltier *et al.*, 2008). The *Rhagovelia* spp. samples from all the twelve sampling sites had OCPs although in different levels, which demonstrates the robustness of using macroinvertebrate FFGs as bioindicators of environmental quality. Similarly, due to their intimate relationship with sediments which act as sinks for pollutants, they easily bioconcentrated the OCPs. The same reasons have been advanced where it is widely believed that macroinvertebrates are good indicators of pollution because they are bottom dwellers, which make them more efficient to bioaccumulate pollutants (Nyakeya *et al.*, 2022). Their ability to bioconcentrate toxicants also depends on the geochemical background of the sediments (Turner, 1995).

Rhagovelia spp. falls under the predator FFG of macroinvertebrates hence a high probability of having predated on other FFGs thus increased chances of biomagnification. Depending on the level of macroinvertebrate FFGs, there are different pathways through which OCPs can find their way into the body. Filterers can access them via gills and the nutritional requirements such as filtration in the water column, grazer-scrapers through foraging on periphyton and phytoplankton, collector-gatherers by collection and gathering of fine particulate matter, shredders via feeding on coarse particles of organic matter deposited in/on sediments, and lastly predators through preying on other invertebrates (Mebane *et al.*, 2020). OCPs are among hydrophobic contaminants often detected in aquatic organisms as *Rhagovelia* spp. and can be magnified by trophic interactions, beginning with those at the base of the food web. Therefore, OCPs may have been sorbed to existing algae cells consumed by the grazing macroinvertebrates/zooplankton which in turn might have been preyed upon by *Rhagovelia* spp. in the next trophic level. During sorption or grazing, OCPs are portioned to lipid rich organs and tissues leading to their bioaccumulation (Bard, 1999). There is high efficiency experienced during the OCPs transfer from one trophic level to another resulting to biomagnification at each level (Larsson *et al.*, 2000). Therefore, the concentration levels witnessed in different stations could be explained by transfer of OCPs to *Rhagovelia* spp. via other macroinvertebrate FFGs at the lower trophic levels.

According to Dallinger and Rainbow (1993) the concentration of toxicants in microbenthic invertebrates is proportional to the pollutant uptake, transport, utilization, and excretion, and varies with each taxa, genus and/or species. The concentration of OCPs in *Rhagovelia* spp. could have been bioconcentrated or bioaccumulated depending on the bioavailability of the different pesticides from dissolved and particulate organic matter and the ability of the OCP escaping from the macroinvertebrate (Franzle, 1995). Moreover, the variations in OCP concentration that was witnessed from one station to another could be as a result of sex, size and age. This is in agreement with Pastorino *et al.* (2020b), who opined that on a temporal and spatial scale, the amounts of OCPs among the group of species/taxa of macroinvertebrates taking refuge in a given ecosystem is likely to vary on the basis of early history strategies such as size, age, sex, and developmental stage of the individuals. In addition, Pros (1981) and Hare (1992) confirmed that related taxa, up to species level but under the same genus, and inhabiting a homogeneous system could bioconcentrate different levels of OCPs.

Conclusion and recommendations

The aim of this study was to assess the distribution of OCPs in macroinvertebrates FFGs of *Rhagovelia* spp. in the tropical estuarine ecosystems of South Coast, Kenya. Sixteen OCPs were recorded from *Rhagovelia* spp sampled in all the twelve study sites, with varying concentration levels. The ANOVA results underscored the multifaceted nature of environmental dynamics, with 'station' exerting significant influences on OCPs concentrations in *Rhagovelia* spp. The observed interaction effect further accentuated the complexity of environmental processes. Overall, these results provided valuable insights into the factors influencing OCPs levels in *Rhagovelia* spp. and can be used to guide future research and environmental management strategies. These findings offer valuable insights for environmental monitoring and management efforts, emphasizing the need for targeted interventions to mitigate chemical exposures and safeguard environmental health. It is on the foregoing basis that the null hypothesis, which stated that there is no significant difference in the distribution of OCPs by aquatic macroinvertebrates FFG of *Rhagovelia* spp. between the sampling stations was rejected. The statistical analysis revealed that each station played a crucial role in determining the levels of OCPs in *Rhagovelia* spp. due to both environmental factors, early life history strategies of the tested bioassay organism, and different sources of OCPs as influenced by anthropogenic activities. The study recommends for the application of macroinvertebrate FFG of *Rhagovelia* spp. in biomonitoring of estuarian ecosystems. Further research may delve into elucidating specific drivers behind spatial variations in OCPs concentrations from *Rhagovelia* spp. to facilitate informed decision-making for sustainable environmental stewardship. However, to fully understand the impacts of OCPs in the environment, we strongly recommend the use of all/different FFGs of macroinvertebrates such as grazers, collector-gatherers, filterers and shredders in order to bring out the general behavior of these pesticides along the food web.

Ethical approval

The authors complied with the provisions of KMFRI research policy that spells out the code of conduct for researchers. KMFRI is a state corporation established in 1979 by the Science and Technology Act, Cap. 250 of the Laws of Kenya. The Act was repealed in 2013 by the Science, Technology and Innovation Act, no. 28, which recognizes KMFRI as a national research institution under section 56, fourth schedule. Further, the study was approved by the Institutional Scientific and Ethics Review Committee (ISERC) of Kisii University, Ref. No. KSU/ISERC/OO11/7/24.

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Unravelling the causes of the current wild fish kills in Kisumu Bay fishery of Lake Victoria, Kenya

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Abstract

Recurrent fish kills in Kisumu Bay, Lake Victoria, Kenya, threaten both ecological stability and local livelihoods. This study investigates the drivers of recent fish mortality events through field surveys and water quality analysis across key stations, including Kisat River mouth, Coca-Cola discharge zones, and the control station. Results revealed severe hypoxia (dissolved oxygen [DO] < 2.5 mg L^{-1}), far below the 6–8 mg L^{-1} threshold required for fish survival, alongside hyper-eutrophic conditions marked by elevated ammonium (NH_4^+ > 1.5 mg L^{-1}), total nitrogen (TN > 40–50 µg L^{-1}), and phosphorus (TP >700 µg L^{-1}). Chlorophyll-*a* concentrations exceeded 100 µg L^{-1}, indicating prolific algal blooms linked to nutrient overloading, possibly from industrial effluents, agricultural runoff, and untreated sewage. Spatial-temporal analysis identified the lowest DO levels during algal decomposition phases, exacerbated by an oil layer near docking sites, which could have impeded gas exchange and coated fish gills, intensifying respiratory stress. Nitrite peaks (21.12 mg L^{-1}) and ammonium spikes signaled toxic pollution from wastewater, while Secchi depth measurements inversely correlated with algal biomass, confirming turbidity-driven hypoxia. The study attributes fish kills to possible synergistic effects of nutrient pollution, climate-driven temperature rises (27.26°C on average), and inefficient waste management. The study recommends enforcing industrial effluent regulations, expanding wastewater treatment infrastructure, and reclaiming wetlands to mitigate runoff. This work provides a framework for addressing eutrophication-driven fish mortality in tropical freshwater ecosystems, advocating for integrated watershed management to sustain Lake Victoria's fisheries and socio-economic resilience.

Keywords: fish kills, hypoxia, eutrophication, nutrient pollution, Lake Victoria, algal bloom

Introduction

Fish kills, defined as the sudden localized large-scale death of fish in either marine, estuarine or freshwater environments are a common occurrence (Meyer and Barclay, 1990) and can range from several individuals to millions of fatalities per incident (Holmlund and Hammer, 1999). While some fish kills may occur naturally, due to extreme seasonal temperatures, parasites and diseases, human-induced changes and pollution have amplified their frequency and scale globally. A majority of the fish kills are linked to human activities emanating from industrial, municipal, agricultural and transport-related processes. Specific causes include chemical spills, manure, pesticide application, sewage and nutrient enrichment, and harmful algal blooms (La and Cooke, 2011). Despite the widespread occurrence, very few countries have established regional or national frameworks to systematically track the prevalence, magnitude, and underlying causes.

Over the years, Lake Victoria has undergone drastic environmental changes mainly due to anthropogenic activities, which have likely contributed to recurring fish kills. The transformation began with the advent of the railway, establishing the region as a special economic zone engaged in global trade (Graham, 1929). A wave of settlers arrived, drawn by the Lake's resources and fertile catchment area, leading to the conversion of forests, natural vegetation, and wetlands into agricultural land for cash crop plantations (Balirwa *et al.,* 2003). As a result, population growth around the Lake surged, increasing from 8.7 million in 1960 to over 42 million (Nyamweya *et al.,* 2020). Over the years, poor land-use practices and the extensive use of agrochemicals (Peters and Meybeck, 2000) contributed to soil erosion, siltation, and declining water transparency (Sitoki *et al.,* 2010). Additionally, deforestation, sedimentation, and nutrient loading led to eutrophication and frequent algal blooms, further impacting water quality and fish populations. The first eutrophication event is suspected to have occurred as early as the 1950s in the Kenyan waters of Lake Victoria and later on spread into the Uganda and Tanzanian regions. Studies indicate that during this period there was a shift in phytoplankton composition from diatoms to cyanobacteria. This was accompanied by deep-water oxygen depletion (anoxia) which intensified around this time. (Lehman, 1998; Verschuren *et al.,* 2002; Stager *et al.,* 2009). Urbanization and industrialization have exacerbated pollution, with untreated sewage and industrial effluents further degrading water quality (Balirwa *et al.,* 2003). Additionally, climate change has intensified these impacts through altered rainfall patterns, stronger storm events, and rising water temperatures, affecting dissolved oxygen levels and increasing the frequency and severity of fish kills.

The Nyanza Gulf has a history of fish kills with a notable event documented in 1984 after a violent storm that resulted in mass mortalities exceeding 400,000 fish, which collectively weighed over 2,400 tons. The casualties were Nile perch (*Lates niloticus*) and Nile tilapia (*Oreochromis niloticus*). Several factors were attributed to this mass mortality event such as low dissolved oxygen, high levels of suspended matter in the form of detritus and algae which clogged the gills of fish, low pH and algal bloom (Ochumba, 1990). Other factors include oxygen depletion caused by agricultural runoff which may contain toxic chemicals due to poor farming practices, ammonia toxicity and heavy rainstorms which increase runoff into the water body (La and Cooke, 2011).

Persistent occurrence of this phenomenon poses significant economic risks, especially by depleting populations vital to commercial and recreational fisheries (Holmlund and Hammer, 1999). For example, the 2022 fish kill incident in Kisumu and Homa Bay resulted in nearly a billion shillings ($7.2 million) in losses (Odhiambo, 2023). Similarly, the 2024 fish kills at Mulukoba where approximately 50 tonnes of fish were lost, translated to over 5 million shillings in losses (Opanda, 2024).

The number of distress calls on fish kills from stakeholders has escalated in recent months, with three calls within November and January, which is quite unusual. It is against this backdrop that this study was undertaken to investigate the current wild fish kills in Kisumu Bay, Kisumu County, and demystify their underlying causes to provide applicable mitigation measures.

Materials and methods

Study Area

The study on fish kills was undertaken in the Kenyan waters of Lake Victoria consisting of the Nyanza Gulf (Winam Gulf) which forms the major portion of Kenya waters (Fig. 1). The Kenyan side of the Lake covers an area of 4,100 km^2, with a length of about 60 km and width varying between 6 and 30 km and lies between 34° 13′ and 34° 52′ East of latitude 0°, 0° 4′ and 0° 32′ South of the Equator. The Gulf has an average depth of 6-8 m and a maximum depth of 70 m (in the open waters) (Odada *et al.,* 2004; Aura *et al.,* 2018). Nyanza Gulf at irregular periods of the year experiences intermittent fish kills affecting either cage or wild fish. Sampled stations were determined at accessible points within areas affected by reported fish kills. Global Position-

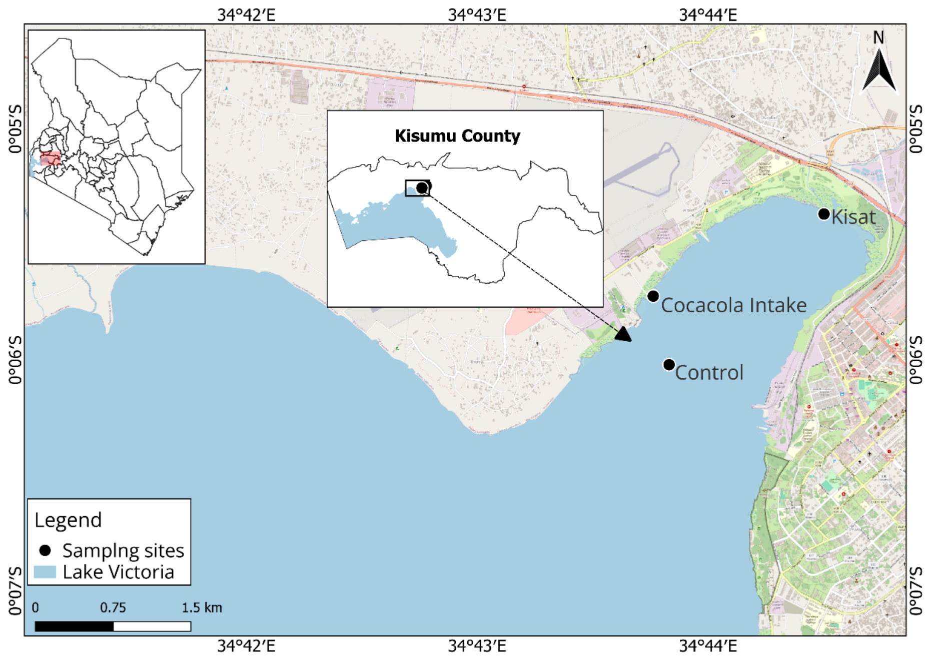

Figure 1. Map of Kisumu Bay, Winam Gulf, showing areas sampled for reported fish kills (Source: Owoko W., 2025)**.**

ing System (GPS) locations (GPS Coordinates) thereafter were marked using a hand-held GPS tool as waypoints and salient attributes of the sites recorded prior to sampling.

Physico-chemical parameters

After calibration, *in situ* physico-chemical water quality parameters of Temperature (°C) and Dissolved Oxygen (DO) (mg L^{-1}) measurements were achieved by use of a portable electronic YSI multi-parameter meter to log in water quality data down the depth of the water column. Acid-washed 500 ml plastic bottles were prepared for preservation of water samples for both soluble and non-soluble nutrients fractions of Soluble Reactive Phosphates (SRP), Nitrates, Ammonium, Nitrites and Silicates. Additionally, water samples for Chlorophyll-a, Total Nitrogen and Total Phosphorous were immersed in a cooler box at temperatures of about 4°C and transported for membrane filtration of a volume of lake water through Whatman® GF/C filters which were then used to determine the difference per unit volume of sample and digestion in KMFRI laboratory using methods adopted from APHA (2005) and Sasaki *et al.* (2005).

The analyzed nutrient compounds were Nitrates-N, Ammonium-N, Nitrites-N, Soluble Reactive Phosphorous (SRP) and Silicates. Secchi depth (m) measured with a standard Secchi disk of 20 cm diameter and with quadrants painted in black and white was recorded. Secchi depth is derived as the average of the depth at disappearance and that of reappearance of the disk in water. General environmental observations about the target stations like the maximum depth of the sampling site, time of sampling, weather conditions and station features, were documented. Water samples for chlorophyll-*a* data were filtered using GF/C filters, wrapped in aluminium foil and stored in a desiccator for onward seston solvent extraction and spectrophotometric analyses using methods described by Sasaki *et al.* (2005). Data was collected in response to distress calls on November 14th 2024 (1st sampling), January 16th 2025 (2nd sampling) and January 28th 2025 (3rd sampling).

Data Analysis

Inferential and quantitative methods were employed to assess spatial-temporal variations in water quality parameters and their linkages to fish mortality. Primary data collected from three sampling stations (Kisat River mouth, Coca-Cola, and Control site) during three periods (November 2024 to January 2025) were cataloged in Microsoft Excel 2010. The averages for dissolved oxygen (DO), temperature, nutrient concentrations (NH_4^+, NO_3^-, NO_2^-, TN, TP, SRP), chlorophyll-a, and Secchi depth were plotted using R software version 4.4.3.

Results and discussion

Trends in temperature (°C) and dissolved oxygen (DO, mg L^{-1}) levels across the different sampling stations over three sampling periods are illustrated in (Fig. 2). These parameters are essential for aquatic life; temperature affects metabolic rates, oxygen solubility due to its inverse relationship, and biochemical processes, whereas DO is critical for fish survival (Wetzel, 2001; Kalff, 2002). Though the DO levels fluctuate, there is a general trend of low concentrations across the sampling sites. Only the control sites exhibited desirable levels of 5 - 7 mg L^{-1}. The overall mean value for DO was 4.09 ± 2.05 mg L^{-1}, with a range of 5.21 mg L^{-1}, which is not desirable as fish generally require DO levels of between 6 – 8 mg L^{-1} to thrive (U.S. EPA, 1986; FAO, 2015). Coca cola intake point consistently exhibited anoxic conditions during the second and third sampling periods with average DO levels of 1.71 and 1.77 mg L^{-1} and 2.93 and 1.99 mg L^{-1} at the Kisat River mouth.

The mean temperature observed across the sites for the three periods was generally warm at 27.26 ± 0.66°C with a range of 1.96°C. This has an effect of reducing the solubility of oxygen in water and also accelerating microbial decomposition of organic matter, therefore consuming oxygen and exacerbating anoxia (Paerl and Huisman, 2009). The critically low DO levels at Coca cola and Kisat River mouth were likely due to a combination of the effects of high temperatures and nutrient pollution (phosphorus and nitrogen) from sewage, agricultural runoff, and industrial wastes (Dodds and Smith, 2016). Such low DO levels are stressful to fish and can cause mass mortalities (Diaz and Rosenberg, 2008).

Trends in nitrogen compounds (ammonium, nitrates, nitrites, and total nitrogen) and soluble reactive phosphorus (SRP), total phosphorus (TP), and silicate concentrations at three sampling stations over the three sampling periods are presented in Figure 3 and 4, respectively. A sharp increase in nitrate and nitrite levels was observed in the 2nd sampling, particularly at Kisat River mouth (82.03 μg L^{-1} and 21.12 μg L^{-1}) and Coca cola (94.15 μg L^{-1} and 19.91 μg L^{-1}). This increase was likely due to an influx if nitrogenous compounds, likely due to runoff, sewage and industrial discharge or sediment disturbance. These elevated nitrite levels may be toxic to fish by disrupting oxygen transport in the blood system, a condition referred to as methemoglobinemia, also known as "brown blood disease" (Jensen, 2003). This was followed by a

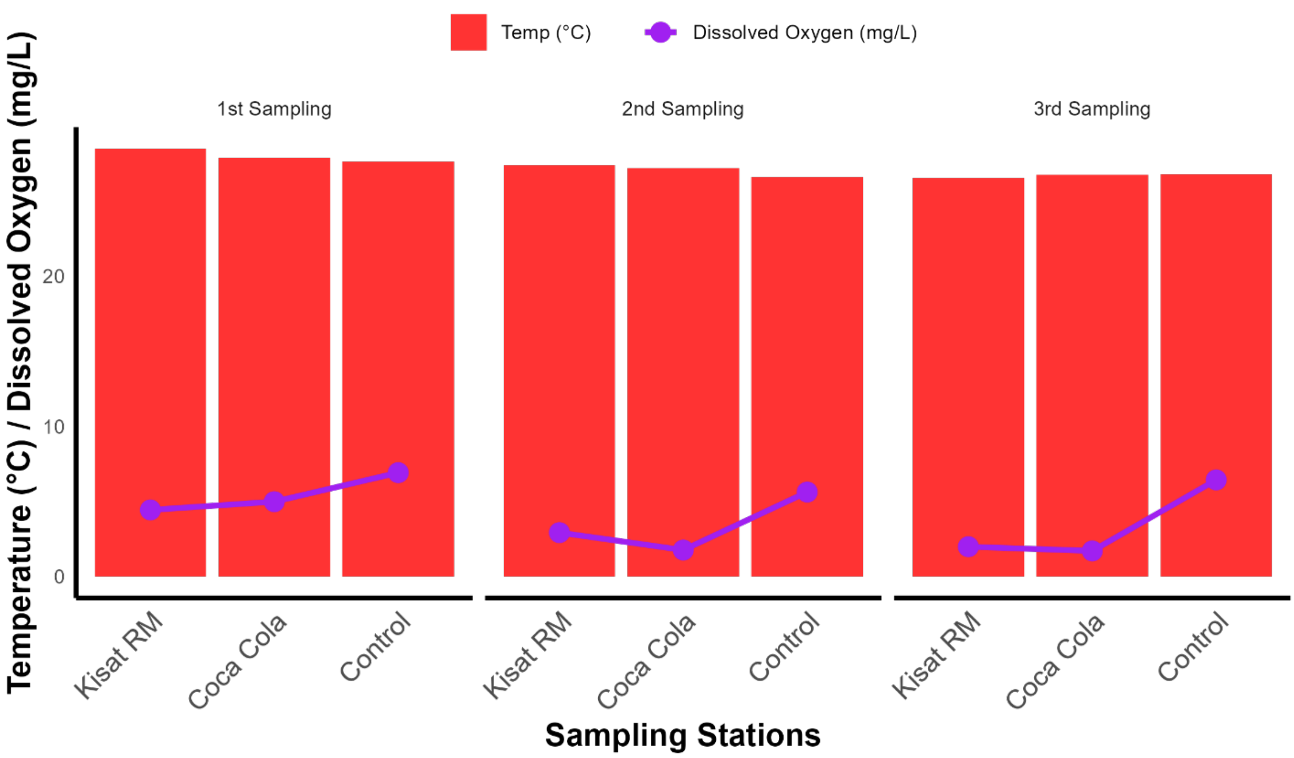

Figure 2. Dissolved Oxygen (mg L^{-1}) and Temperature (°C) trends across stations during the sampling of fish kills studies at the Kisumu Bay Lake Victoria, Kenya.

significant decline in nitrate and nitrite concentrations during the 3rd sampling session, presumably due to uptake by phytoplankton, and the dilution effect of water movement by currents. The control station exhibited much lower concentration across all the sampling periods, indicative of localized pollution at the Kisat River mouth and Coca Cola stations.

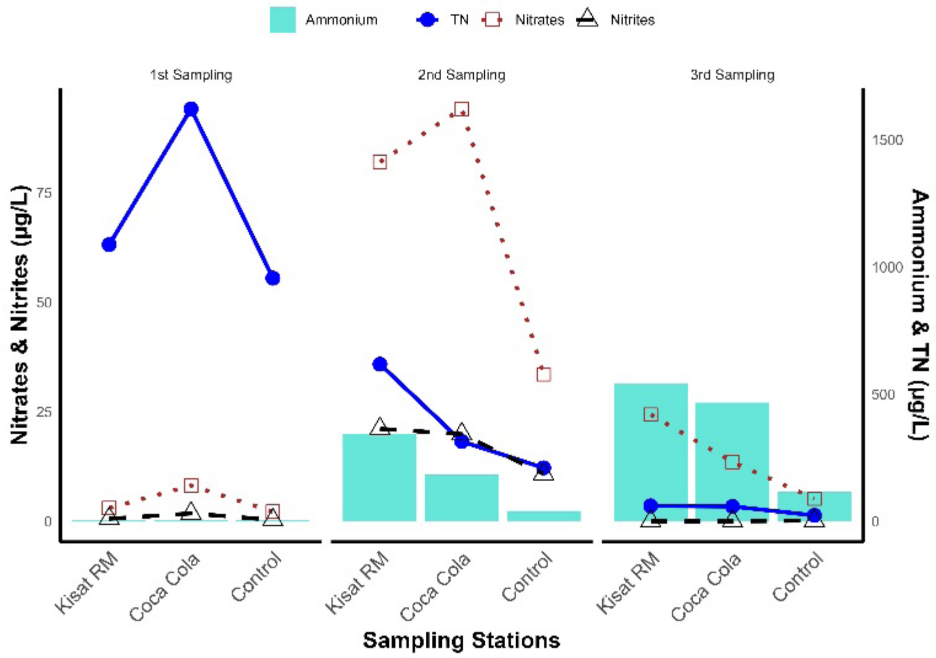

Figure 3. Trends in (Total Nitrogen, µg L^{-1}), Ammonium (µg L^{-1}), Nitrates µg L^{-1}) and Nitrites (µg L^{-1}) concentrations across stations during the sampling of fish kills studies at the Kisumu bay Lake Victoria, Kenya.

A significant peak was observed in Ammonium concentrations in the 2nd sampling at Kisat River mouth and Coca Cola stations. This coincided with high levels of total nitrogen (TN) indicating possible anthropogenic pollution emanating from sewage and waste water discharge (Camargo and Alonso, 2006), agricultural runoff from upstream containing ammonium and organic nitrogen-rich fertilizers (Carpenter *et al.,* 1998). The TN levels drastically dropped in the 3rd sampling presumably due to dilution or microbial uptake. However, the ammonium levels continued to increase, indicating incomplete nitrification, which is usually associated with anoxic conditions (Diaz and Rosenberg, 2008), synonymous with fish kills. Figure 2 shows that the DO levels were anoxic during these periods. Both ammonium and TN levels were way above the globally recommended standards of 1.5 mg L^{-1} (EPA, 2013) and 40-50 µg L^{-1}, respectively (U.S. EPA, 2013; OECD, 1982).

Soluble Reactive Phosphorus (SRP) varied across the sampling stations, with an increasing trend from the 1st to the 2nd sampling periods. The highest SRP values were recorded at the Control station in the 3rd sampling period. Total Phosphorus (TP) had more pronounced peaks in the first sampling period, suggesting anthropogenic sources from wastewater discharge and runoff from agricultural lands (Sitoki *et al.,* 2012). A decrease between the 2nd sampling and a further peak in the 3rd sampling period followed this. The decline experienced in the 2nd sampling, may hhave been due to dilution from increased water flow or biological uptake by phytoplankton (Paerl and Otten, 2013). Elevated phosphorus (TP and SRP) and TN levels are strongly associated with eutrophication in freshwater systems (Dodds and Smith, 2016). The levels recorded during the three sampling periods beyond the acceptable threshold (40-50 *µ*g L^{-1}). Such levels promote excessive growth of phytoplankton, resulting in algal bloom and as the organic matter from the bloom decomposes, it utilizes the already depleted dissolved oxygen, resulting in fish kills due to hypoxia (Randall and Tsui, 2002; Diaz and Rosenberg, 2008).

Figure 5 presents trends in alkalinity, hardness, Chlorophyll-a, and Secchi depth across different sampling stations over the three sampling periods. Chlorophyll-a exhibited fluctuating concentrations with the highest peak in the 3rd sampling period, particularly at Kisat and Coca cola sta-

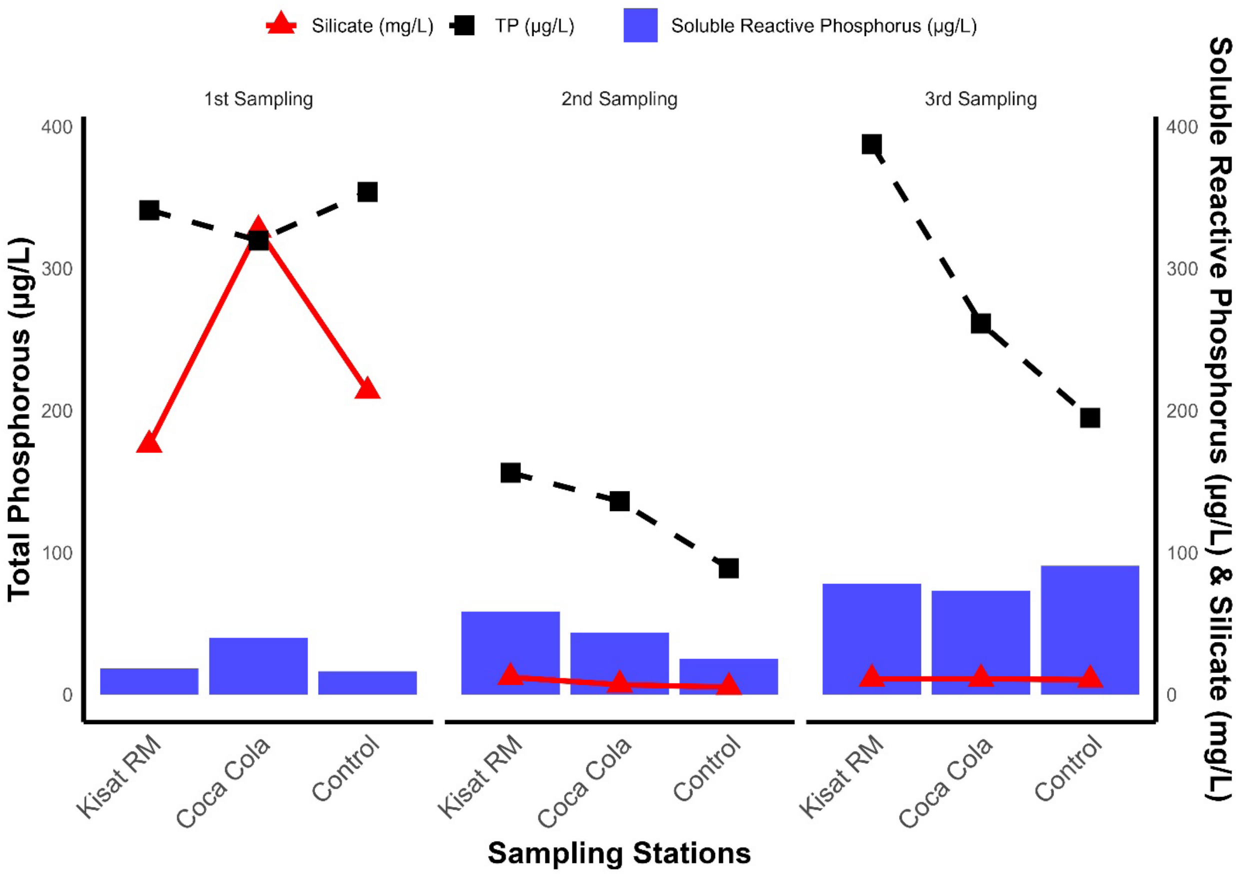

Figure 4. Trends in total phosphorous (µg L-1), soluble reactive phosphorus (µg L^{-1}); and silicates (mg L^{-1}) concentrations during the sampling for fish kills studies at the Kisumu Bay Lake Victoria, Kenya.

tions. These concentrations were beyond the acceptable standards of 1-2 µg L^{-1} (OECD, 1982; U.S. EPA, 2000) indicating eutrophication (Paerl and Otten, 2013). This increase in chlorophyll-a levels correlates with the high phosphorus levels observed as illustrated in Figure 3 during the same sampling periods, ascertaining that phosphorus is a key driver of phytoplankton growth (Smith *et al.,* 1999).

Secchi depth (m), a measure of water clarity, exhibited an inverse relationship with chlorophyll-a concentrations. Elevated chlorophyll-a levels corresponded to reduced Secchi depth readings, indicating greater turbidity caused by algal proliferation, particularly at Kisat and Coca Cola stations. Elevated chlorophyll-a levels alongside reduced Secchi depth measurements signal heightened primary productivity in the water column, a phenomenon strongly linked to nutrient enrichment (Paerl and Hall, 2016). This surge in phytoplankton biomass often drives excessive organic matter accumulation, which, upon decomposition, can deplete dissolved oxygen levels, resulting in hypoxic or anoxic conditions that threaten aquatic ecosystems (Diaz and Rosenberg, 2008).

Conclusion and recommendations

Most of the physico-chemical parameters in the sampled stations at the sampling times exceeded globally recommended standards, rendering the environment unsuitable for fish and aquatic life. Critically low dissolved oxygen indicated anoxic conditions likely driven by nutrient overloading and organic matter decay, a known precursor for fish mortality. High ammonia (NH3) levels further evidenced microbial decomposition of organic waste, pointing to potential wastewater contamination. The high total nitrogen (TN) and

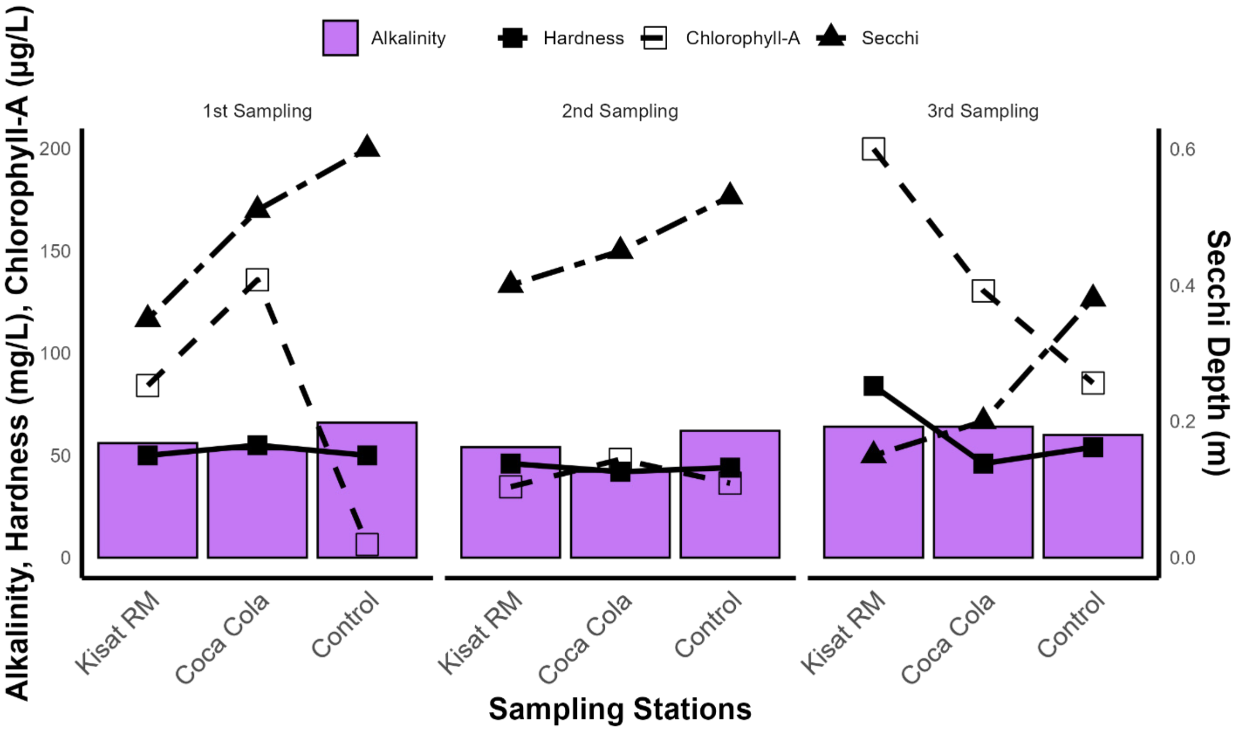

Figure 5. Trends in total alkalinity (mg L⁻¹), total hardness (mg L⁻¹), *chlorophyll-a* (µg L⁻¹) and *Secchi* depth (m) across stations during the sampling for fish kills studies at the Kisumu bay Lake Victoria, Kenya.

total phosphorus (TP) concentrations across all stations indicated nutrient pollution probably from industrial effluents, agricultural runoff, and sewage discharge. Concurrently, extreme chlorophyll-a levels signaled eutrophication and algal blooms, which deplete oxygen via nighttime respiration and post-bloom decomposition, forcing fish to surface for air. These conditions were worsened by an oil layer which was observed, which may have impaired gas exchange by forming a physical barrier and coated fish gills, intensifying respiratory stress and compounding the hypoxic stress caused by algal blooms. Collectively, these factors may have led to the fish kills. It is therefore recommended that:

1. associated companies periodically present and implement control measures that have been put in place to minimize oil spill and untreated sewage discharges;
2. periodical random visits be conducted by the relevant agencies for inspection of point sources of pollution into the Lake and assessing their efficiency and performance;
3. improved efforts in development of waste water treatment facilities be executed by associated companies;
4. implementation of wetland reclamation to filter runoff before reaching the Lake should be prioritized;
5. enforcement of the regulatory frameworks in place should be improved to reduce industrial and domestic pollution sources; and
6. continuous monitoring should be done by the scientists to inform the relevant agencies for mitigation.
7.

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Catch and effort composition and management implications of Lake Baringo's small scale fishery

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Abstract

Small scale fisheries in Africa especially within the tropics are an important source of livelihoods to millions of people who depend on the fish value chain for employment. The fishing sector plays an important role in food security by provision of essential minerals and proteins. However, with increased population growth rate, there has been a rapid demand for fish in most of the inland lakes in Kenya, including Lake Baringo. This has led to increased exploitation of the fishery resources as the fishers' target to maximize benefits. In order to come up with sound management of this resource, catch and effort data was collected through standard operating procedures for fish catch assessment survey (CAS). This was done in 6 landing beaches of Lake Baringo in 2024 by means of questionnaires and personal observations. Data collected included number of canoes that went fishing on the sampling day, gear types, fish species and catch landed among others. Results indicate that majority of the longline fishers used an average of 275 ± 6.0 hooks of sizes 8 and 9 to catch *Protopterus aethiopicus* and *Clarias gariepinus,* whose composition was 17.6% and 9.2%, respectively. Gill nets of stretched mesh sizes 25 mm to 125 mm were used, with 62.5 mm and 75 mm nets being most used at 35% and 25%, respectively. The mean sizes of *Oreochromis niloticus* was 19.5 ± 6.5 cm, 22.2 ± 12.6 cm for *Labeobarbus intermedius*, 39.7 ± 12cm for *C. gariepinus* and 79 ± 10.5 cm total length for *P. aethiopicus*. Total fish landings were estimated at 345 tonnes, with a beach value of KES 63 million. It is recommended that fishery regulations enforcement should be enhanced especially on fishing effort to avoid overfishing; and capacity building of BMUs and other stakeholders on sustainable management of the fishery should be done regularly.

Keywords words: management, catch assessment survey (CAS), catch per unit effort (CPUE), catch composition, fishing gear, beach value

Introduction

The fisheries industry occupies an important role in the global economy and human diets. It is a key foreign exchange earner, enhances food security and provides employment opportunity to many people. Around 100 million people are estimated to be involved in the small scale post-harvest sector which involves fish processing, transport and marketing. Fish production has increased immensely at the global level from 20 million tonnes in 1960 to about 214 million tonnes in 2020 (FAO, 2022). The global increment of fish consumption from 9.9 kg in the 1960s to 20.5 kg in 2020 has increased the world per capita fish consumption. This has been attributed to population increase, more incomes, urbanization and improved distribution of fish products (FAO, 2022). The vast majority of the world's fishers and fisher farmers live in the developing countries where they mostly use small crafts and boats with limited capacity of catch landings (FAO, 2022). Freshwater fisheries are an important source of livelihood and income to millions of the world's poorest people, and also contribute to the overall economic wellbeing of many developing countries (FAO, 2018).

Small scale- fishing in East Africa has been a source of food security to the people and employment opportunities supporting livelihoods of about 3 million people (LVFO, 2009). In the recent years the value of catch at some beaches is estimated at more than USD 550 million and export value of USD 260 million. The fishery produce in East Africa is estimated to be 1 million tonnes per annum, of which 14.8 % is from Kenya, 66.6 % from Tanzania and 18.6 % from Uganda (LVFO, 2013). This indicates that fish catch has been increasing over the years, influencing people's livelihoods and reducing vulnerability to poverty. Kenya's National Nutrition Action Plan (2018-2022), promotes fisheries as one of the sectors that can contribute to national nutrition goals under Kenya's Vision 2030: The national long-term development blueprint for transforming Kenya into an industrializing middle income country by 2030, recognizes the importance of the contributions of the fisheries sector (Kenya Vision, 2030).

Small-scale and industrial fishing sector in Kenya produces fresh and processed fish for domestic and export markets, accounting for about 0.5% of the country's Gross Domestic Product (GDP) (KCDP, 2013). Despite its limited contribution to the country's GDP, the fisheries sector generates employment for over two million Kenyans through fishing, boat building, equipment repair, fish processing, and other ancillary activities (FAO, 2018).

Catch and effort composition data have been utilized to come up with informed management decisions for sustainable utilization of the resources. When catch data is combined with information on fish prices, it can be used to estimate the gross value of production. This provides an indication of the economic importance of the fishery relative to other fisheries or sectors. This is important for helping shape policy and for development planning purposes (KCDP, 2013). Catch assessment surveys (CAS) aim at estimating stock abundance from catch landings and effort data through relative indices such as catch per unit effort (CPUE).

Fish landings in Lake Baringo have experienced oscillations in catches over the years which have reduced per capita earnings of the fishermen. The state of poverty in the region has also led to many young people who drop out of school to seek any available source of livelihood including illegal fishing using undersized nets. This study therefore aims to employ catch and effort data to recommend prudent management of the Lake Baringo fishery.

Materials and methods

Study area

The study was conducted in Lake Baringo, a shallow freshwater lake in the Eastern Rift Valley of Kenya (Fig. 1). The Lake lies between latitudes 0°30′ N and 0°45′ N and longitude 36° 00′ E and 36°10´ E., approximately 60 km North of the equator at an altitude of 975 m above mean sea level. It is also a source of freshwater used for domestic purposes especially drinking and livestock watering; and supports a substantial fishery in a semi-arid area. Its fishery comprises of four commercially important species (*Oreochromis niloticus, Clarias gariepinus, Protopterus aethiopicus* and *Labeobarbus intermedius*), while *Labeo victorianus* rarely appears in fishermen's catches (Mugo et al., 2022). The decreased fish diversity is thought to be due to overfishing and limnological changes (Hickley et al., 2004).

The Lake surface is reported to cover slightly over 130 km^2, with wide fluctuations in water levels due to climatic influences (Kallqvist, 1987; Hickley *et al.*, 2004). The catchment area is about 6820 km^2 and includes a large part of the Western escarpment of the Kenyan Rift Valley where most of the water is derived from.

The climate of the region is characterized by two rainy seasons with an annual average of about 600 mm (Omondi *et al*., 2014). Due to heavy rains experienced in 2011 in the Eastern African region, the lake water surface increased to 207 km^2. The dry season usually starts from September to February, while the rainy season occurs between March and August (Odada *et al.,* 2006; Omondi *et al*., 2014). The precipitation in the Lake area ranges from about 600 mm on the East and South of the Lake to 1500 mm on the Western escarpment of the Rift Valley. Lake Baringo faces a very high annual evaporation rate of 1650 – 2300 mm (Odada *et al*., 2006). The Lake has no known outflow and is supplied by inflows from seasonal rivers: (Endao, Lokesen, Makutani, Ol Arabel and Molo) and perennial River Perkerra (Omondi *et al*., 2014). The Lake is believed to have an underground seepage which maintains its freshness by losing approximately 108 $m^3 yr^{-1}$ (Dunkley *et al*., 1993).

Data collection

Catch and effort data was collected through a modified design laid out in the approved Standard Operating Procedures for Catch Assessment Surveys for Lake Victoria (LVFO, 2005). The methodology involved two-stage stratified sampling design composed of sample of primary sampling units (PSUs) i.e., the fish landing sites at each selected beach management unit (BMU) followed by selection of Secondary Sampling Units (SSUs) i.e., the vessel-gear type, were randomly selected by a team of Kenya Marine and Fisheries Research Institute (KMFRI) staff who administered 60 questionnaires and key informant interviews. Sampling unit was fishing vessels and gears. Personal observations and recording of catch composition by species, size, weight, fishing gears, craft type and length, value of catch as well as fishing frequency was recorded.

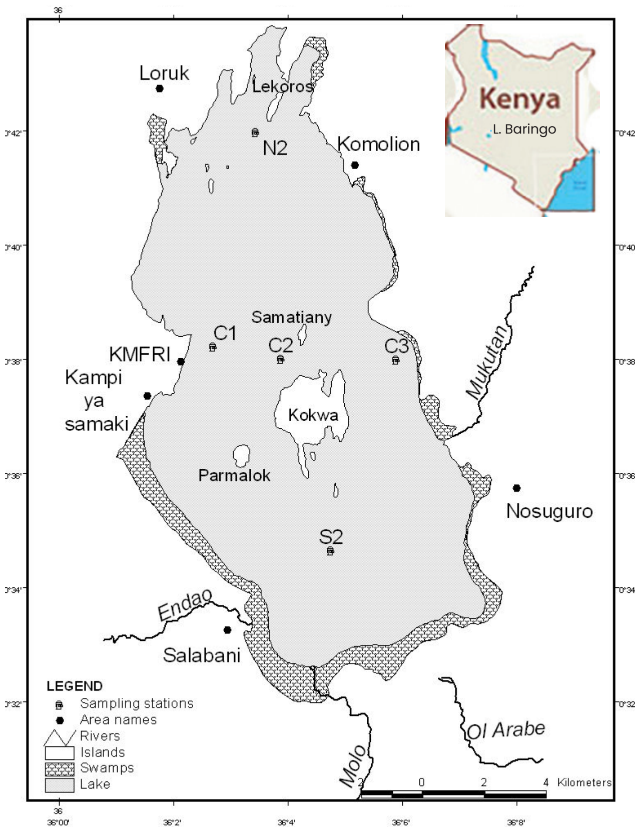

Figure 1. Map of Lake Baringo depicting some of fish lnding sites (Kampi samaki,Loruk, Komolion, Salabani) (Source: Authors)**.**

Data analysis

The raw information and data collected was pooled, entered, cleaned and stored electronically using statistical packages Microsoft Excel 10 and SPSS. The fishing crafts were segregated into effort groups (vessel-gear combinations) and the CAS indicators estimated for each effort group.

The mean fish catch rates (kg^{-1} $boat^{-1}$ day^{-1}) were estimated for each effort group by species using the formulae:

$$CPUE = C / E = q N$$

Where C = catch landed

E = effort deployed

Q = catchability coefficient

N = abundance of the target stock

The total fish catches were estimated using the mean fish catch rates based on the number of vessels enumerated. The beach value of the catch, i.e., the gross income to the fishers, was estimated by raising the estimated total catch in each effort group by the mean unit price of each fish species landed.

Results

Fishing vessels composition

Traditional non-motorized fishing vessels referred in the local language as *Kandich* were the most dominant vessels in Lake Baringo at 60.6% followed by *Sesse* at 21.2% and fiber glass boats at 18.2%. The mean sizes of *Kandich* were 2.5 ± 0.2 m, fiber glass 8.5 ± 0.3 m and Sesse 6.3 ± 0.2 m. The number of crew per *Kandich* was 1 while fiber glass and Sesse had 3 to 4 crew.

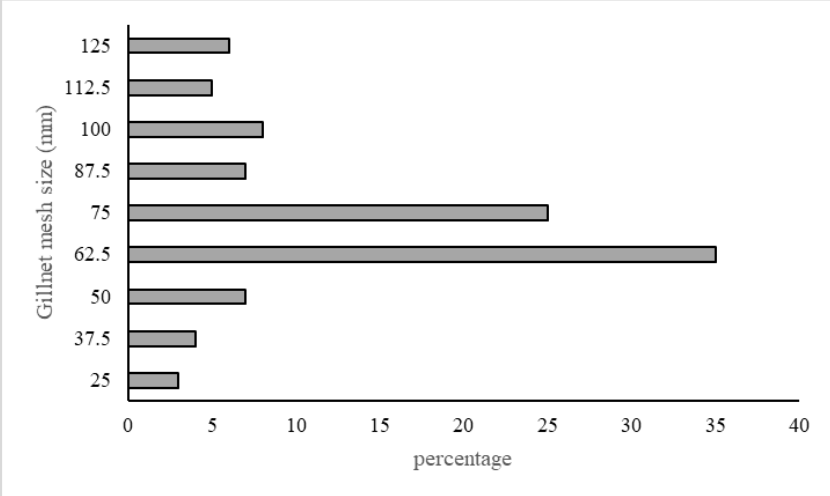

Figure 2. Composition of gill net used in Lake Baringo.

Gear composition

The commercial fishery of Lake Baringo involved use of gillnets (GN) and longlines (LL) as the main gears, while seine nets (SN) were used illegally to catch live fish baits for longlines. *P. aethiopicus* and *C. gariepinus* were caught mainly by LL, while *O. niloticus, C. gariepinus* and *L. intermedius* were targeted by GN. The commonly used hooks were size 8 and 9 with fishers using an average of 275 ± 6.0 hooks. Gillnets used varied from 1" (25 mm) stretched mesh to 5" (125 mm). Mesh size 2.5" (62.5 mm) was the most commonly deployed at (35%) followed by 3" (75 mm) and 4" (100 mm) nets (Fig. 2). The species caught in the various gillnets were *O. niloticus, C. gariepinus* and *L. intermedius.*

Longline gear usage was highest at Salabani (62%) followed by Komolion (60%) and Loruk (54%) beaches. While gillnet usage was highest at Kampi samaki (53%) followed by Kokwa (52%) and Ngenyin (50%). Seine nets were mostly used at Kampi samaki (10%) followed by Ngenyin (8%) and Salabani (7%) (Fig. 3).

O. niloticus (O.n) was the most abundant fish landed in Lake Baringo constituting 69.2% followed by *Protopterus aethiopicus* (Pa) 17.6%, *C. gariepinus* (Cg) at 9.2% and *L. intermedius* (Li) 4% as depicted in figure 4.

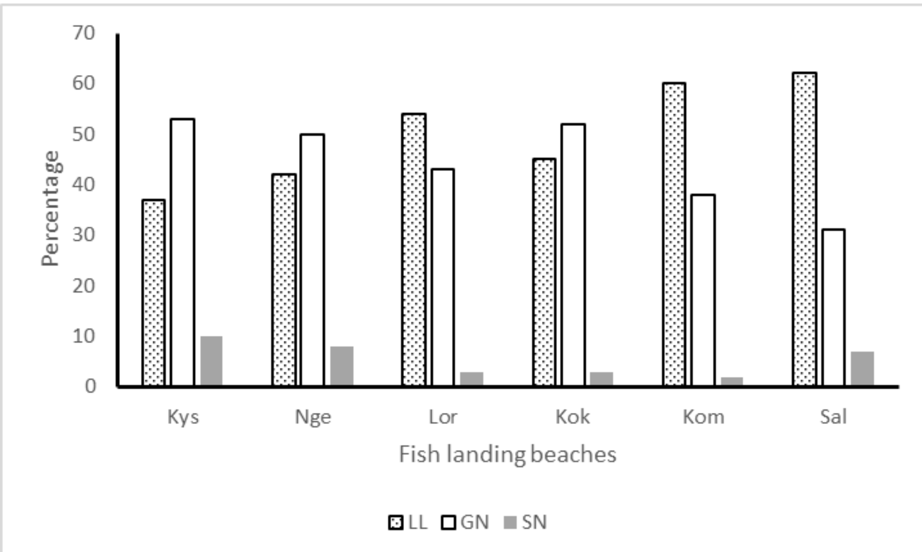

Figure 3. Gear composition in different fish landing beaches (Kys: Kampi Samaki, Nge: Ngenyin, Lor: Loruk, Kok: Kokwa, Kom: Komolion, Sal: Salabani).

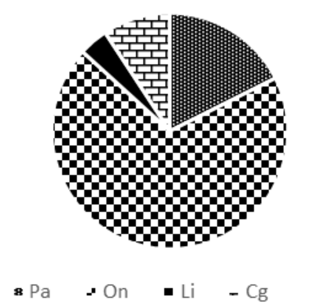

Figure 4. Catch composition of commercial fish species *O. niloticus* (O.n), *Protopterus aethiopicus* (Pa), *L. intermedius* (Li), *C. gariepinus (Cg).*

Catch rates for various fish species

The average catch per boat was highest for *O. niloticus* 82.5 kg^{-1} $boat^{-1}$ day^{-1} followed by *P. aethiopicus* at 21.0 kg^{-1} $boat^{-1}$ day^{-1}, *C. gariepinus,* 11 kg^{-1} $boat^{-1}$ day^{-1} while *L. intermedius* had the lowest catch of 4.8 kg^{-1} $boat^{-1}$ day^{-1} (Fig. 5). The fishers spent an average of 6 days of fishing every week. The total fish landings were estimated at 345 tonnes with a beach value of KES 63 million.

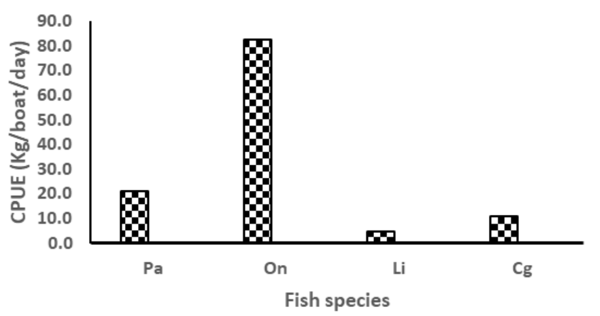

Figure 5. Catch per unit effort of commercial fish species in Lake Baringo Pa *(P. aethiopicus*), Cg (*C. gariepinus*), Li (*L. intermedius*), On (*O. niloricus*).

The mean sizes of commercial fish species is shown in table 1.

Table 1. Mean (± SD) of sizes (Total Length, TL) of commercial fish species.

Fish species	Sample size (n)	Mean size in cm
P. aethiopicus	165	79 ± 10.5
C. gariepinus	193	39.7 ± 12
L. intermedius	265	22.2 ± 12.6
O. niloticus	242	19.5 ± 6.5

Catch prices by species

The average prices of the four commercial species are as depicted in Table 1. *O. niloticus* was the most expensive at KES 230.20 ± 2.70 kg^{-1} followed by *P. aethiopicus* at KES 220.40 ± 2.60 kg^{-1}, while *L. intermedius* was the cheapest at 120.30 ± 1.30 per kg (table 2)

Table 2. Average prices (± SD) of commercial fish species of Lake Baringo

Fish species	Sample size (n)	Mean price (KES kg^{-1})
P. aethiopicus	190	220.40 ± 2.60
C. gariepinus	160	160.60 ± 4.30
L. intermedius	182	120.30 ± 1.30
O. niloticus	200	230.20 ± 2.70

Discussion

Majority of the fishers in Lake Baringo used the traditional fishing vessels known as *Kandich* (60.6%) in their fishing expeditions. This was informed by relatively low construction costs compared to *Sesse* and fibre glass vessels since plant materials for construction of *Kandich* are found within the Lake region. The main gear used by these fishers was longline. Majority of the fishers were located in the beaches towards the Northern area of the Lake: Komolion (60 %) and Loruk (54 %) and Southern part of the Lake, Salabani (62 %), away from the main shopping centre, Kampi Samaki. Their main target was *P. aethiopicus* and *C. gariepinus,* whose CPUE was relatively lower compared to that of *O. niloticus*. The highest contributor to total fish landings was *O. niloticus* at 69.2 %, which was a major shift from the previous years where *P. aethiopicus* and *C. gariepinus* had contributed >85% of total landings, while *O. niloticus* contributed < 5% (Mugo *et al.,* 2018).

The high percentage composition of *O. niloticus* can be attributed to the impact of the overall rise in the Lake level (as from 2020), providing suitable breeding ground and refugia for the juveniles. Studies done in many African lakes, found a positive correlation between increase in lake levels and fish production, whereby increase in lake levels provide suitable breeding grounds and abundant food. (Junk *et al.*, 1989; Kolding and van Zwieten, 2012; Gownaris et al., 2015; Anton, 2016; Kolding et al., 2016). Gillnets were more prominently used at Kampi Samaki and Kokwa beaches, contributing to the landings of *O. niloticus* (with highest CPUE of 82.5 kg^{-1} $boat^{-1}$ day^{-1}), which was >70% that of *P. aethiopicus*, the second-highest landed fish species. Gillnets of 2.5" (62.5 mm) and 3" (75 mm) mesh size were the most commonly used though they are below recommended mesh size of 4 inches (100 mm) and above. This has the potential of reducing the recruitment of many fish species that encounter with this gear.

The catch per unit effort from this study was a bit high, especially for *O. niloticus,* suggesting that fishers might have targeted this species probably due to market demand, as alluded by the high average market price of this species. Catch oer unit effort (CPUE) is commonly used to estimate relative abundance of a population (Harley *et al*., 2001, Maunder *et al*., 2004, and Lynch *et al.,* 2012). These indices of relative abundance are utilized in stock assessment to make decisions of how to manage fish stocks by fisheries managers and policymakers. *O. niloticus* had the highest average market prices of KES 220.40 ± 2.60 followed by *P. aethiopicus* at 160.60 ± 4.30 while *L. intermedius* had the lowest price of 120.30 ± 1.30.

The demand of Lake Baringo fish is evident as fish are distributed to far off markets in Karbarnet, Nakuru, Eldoret and Kisumu. These prices are still relatively low compared to those of similar fish from Lake Victoria (Onyango *et al.*, 2021) Total fish landings for 2024 were estimated at 345 tonnes, with a beach value of KES 63 million. Though the fish landings would seem to be within sustainable levels, the fishing effort may still be high due to illegal, unreported and unregulated (IUU) fishing activities. Climate change and lack of other livelihood alternatives by fishers can also impact negatively on the sustainability of Lake Baringo fisheries.

Conclusion and recommendations

Majority of longline fishers were using an average of 275 ± 6.0 hooks, sizes 8 and 9 to catch *P. aethiopicus* and *C. gariepinus,* whose composition was 17.7% and 9.2%, respectively. Gill nets of sizes 25mm to 125mm stretched mesh were used with 62.5 mm and 75mm nets being most used at 35% and 25%, respectively. The average catch per boat was highest for *O. niloticus* 82.5 kg^{-1} $boat^{-1}$ day^{-1} followed by *P. aethiopicus* at 21.0 kg^{-1} $boat^{-1}$ day^{-1}, *C. gariepinus* at 11 kg^{-1} $boat^{-1}$ day^{-1}, while *L. intermedius* had the lowest catch at 4.8 kg^{-1} $boat^{-1}$ day^{-1}. The total fish landings were estimated at 345 tonnes with a beach value of KES 63 million. It is recommended that fishery regulations enforcement should be enhanced especially on fishing effort to avoid overfishing: and capacity building of BMUs and other stakeholders on sustainable management of the fishery should be done regularly.

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Water quality, ecology of Magadi Tilapia (*Alcolapia grahami*), and socio-economic dynamics in the protected wetland of Lake Elementaita, Kenya

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Abstract

Lake Elementaita is a protected wetland in Kenya that serves a vital ecological function while also supporting local socio-economic activities. This study assessed its water quality, the ecology of *Alcolapia grahami*, and the socio-economic factors influencing its conservation and management. An integrated approach incorporating water quality assessments, fisheries studies, and community surveys was employed to provide a comprehensive understanding of the Lake's ecosystem. The findings revealed that Lake Elementaita experiences wide temperature variations (21°C – 43°C) and high dissolved oxygen levels of up to 16.9 mg L^{-1}. The mean total dissolved solids (8076 mg L^{-1}) and electrical conductivity (15,292.8 µS cm^{-1}) were high. Despite low nitrate (0.03 mg L^{-1}) and phosphate levels (0.09 ± 0.05 mg L^{-1}), chlorophyll-a levels (33.48 mg L^{-1}) were high, indicating substantial phytoplankton biomass in the Lake. Fisheries assessments highlighted the ecological resilience of *Alcolapia grahami*, with population structure analyses showing varying catch rates and an average yield of 0.9 kg hr^{-1}. Length-frequency data indicated positive allometric growth ($b > 3$), suggesting favourable environmental conditions for the species. Additionally, the species exhibited a relatively balanced sex ratio (F:M = 0.92:1). Community surveys revealed a strong socio-economic connection between local communities and the Lake, with frequent engagement in birdwatching and tourism. To enhance the long-term sustainability of Lake Elementaita's water quality, fisheries, and socio-economic activities, the study recommends integrated watershed management, soil conservation, riparian buffer zones, public awareness campaigns, tree planting, and sustainable agricultural practices.

Keywords: water quality, *Alcolapia grahami*, fisheries, socio-economic dynamics, Lake Elementaita, wetland conservation

Introduction

Nestled in the Eastern arm of the Great Rift Valley within Nakuru County of Kenya, Lake Elementaita emerges as a prominent feature, characterized by its shallow, saline waters. Fed by a network of rivers including the Mbaruk, Chamuka, and Mereroni, with the Mereroni River playing a significant role due to Rift Valley faulting dynamics (Githae, 1998). This Lake also receives contributions from hot springs in its Southeastern region and subsurface flows from Lake Naivasha (Muno, 2002). However, the variability in water levels, sometimes leading to the drying up of both the Lake and its feeder rivers (Murimi *et al*., 1993), underscores the dynamic nature of this ecosystem.

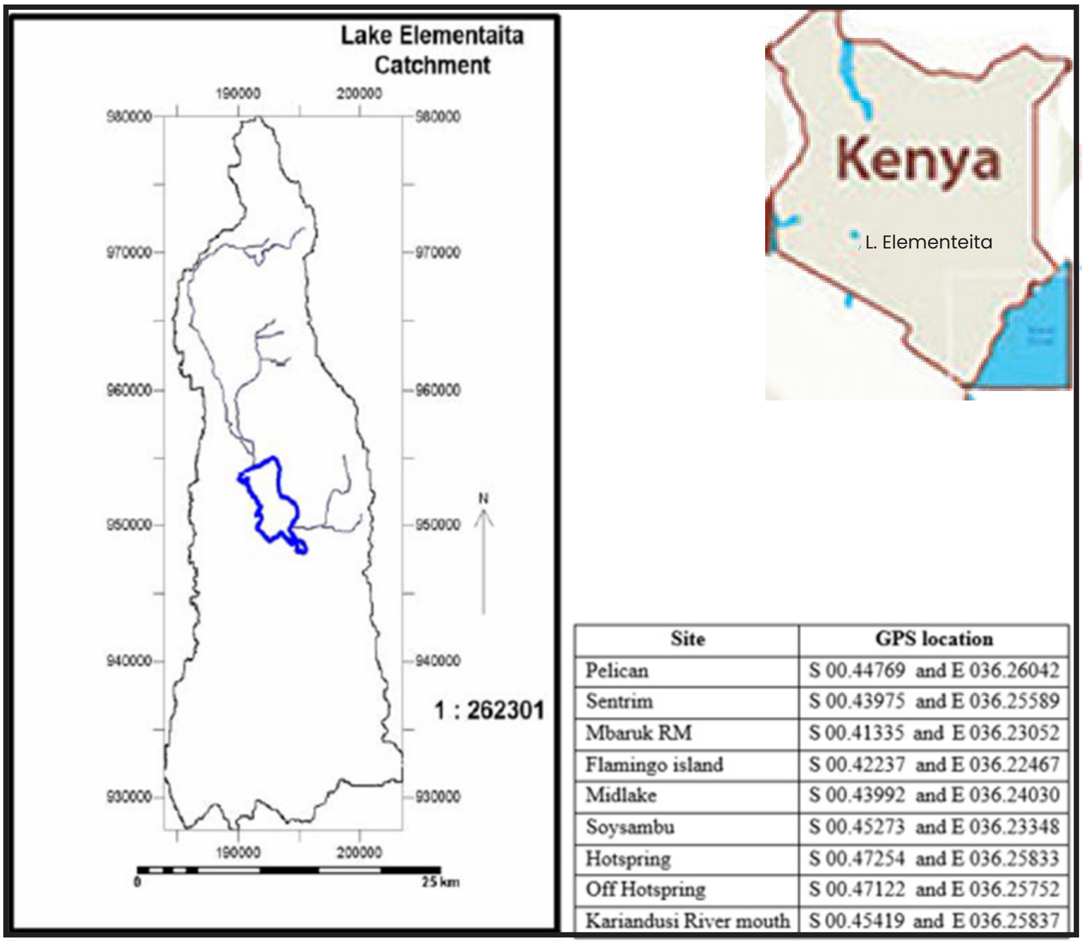
Lake Elementaita is not only a geographical feature but also a vibrant ecosystem, supporting a diverse array of flora and fauna. Its significance is exemplified by its role as a habitat for the pink-backed pelican breeding grounds and a feeding area for the lesser flamingo, which thrives on the blue-green algae *Arthrospira filiformis*. Moreover, human activities such as salt harvesting, game viewing, small-scale farming, and livestock rearing are intricately woven into the fabric of this ecosystem, potentially influencing its water quality and overall ecological health. In the late 1950s, *Alcolapia grahami* fish species was introduced into Lake Elementaita for mosquito control purposes. This species is adapted to the extreme conditions of highly alkaline waters and has thrived in various Rift Valley lakes, often becoming a dominant fish species (Wood *et al*., 2016; Maina *et al*., 2019). Lake Elementaita has drawn attention not only for its ornithological spectacle but also for its diverse vegetation. Acacia and Euphorbia trees dot its landscape alongside various bush and grassland species, although extensive deforestation and land use changes threaten these natural habitats.

The ecosystems of lakes like Elementaita are profoundly influenced by both natural processes and human activities. As societies become more interconnected with their environments, understanding this complex interplay becomes crucial (Mwendwa *et al*., 2015). Researchers such as Berkes and Folke (1998) advocate for integrating social and ecological systems to enhance resilience and sustainability. Carpenter (2008) stresses the importance of scientific knowledge in managing ecosystem services and promoting responsible stewardship. In the face of escalating human population, urbanization, and industrialization, lakes like Elementaita are under increasing pressure. This situation underscores the need for a comprehensive understanding of how ecological dynamics and human behaviors interact. Such understanding is essential for steering practices toward sustainability and ensuring the resilience of these ecosystems. Therefore, this study aimed to explore the interactions between ecological processes and human activities in Lake Elementaita, with the goal of providing insights for effective conservation and management by evaluating water quality, fish stock status, and socio-economic factors.

Materials and methods

Study area

Lake Elementaita is situated in Nakuru County, Gilgil Sub County, and lies between 0°27′ S and, 36°15′ E. Gilgil has a population of 152,102 with Kekopey Centre hosting a population of 15,624 (KNBS, 2009). It lies on the Eastern floor of the Great Rift Valley in Kenya. Geographically, it is surrounded by Nyandarua Hills to the Northeast and Eburru Hills to the South. The Lake is 1,772 m above sea level and is served by rivers Meroronyi, Mbaruk, and Kariandusi (Fig. 1).



Site	GPS location
Pelican	S 00.44769 and E 036.26042
Sentrim	S 00.43975 and E 036.25589
Mbaruk RM	S 00.41335 and E 036.23052
Flamingo island	S 00.42237 and E 036.22467
Midlake	S 00.43992 and E 036.24030
Soysambu	S 00.45273 and E 036.23348
Hotspring	S 00.47254 and E 036.25833
Off Hotspring	S 00.47122 and E 036.25752
Kariandusi River mouth	S 00.45419 and E 036.25837

Figure 1. Map of Lake Elementaita and the GPS points of study's sampling points (Modified from Adeka, et al., 2008).

Data collection

This study was conducted in October 2023. The study employed a mixed-methods approach, combining ecological field surveys, and socio-economic surveys. Quantitative data was gathered through water quality measurements, fisheries assessments, and socio-economic surveys.

Ecological Assessment

The *in situ* measurement of physicochemical parameters, including temperature, dissolved oxygen (DO), total dissolved solids (TDS), pH, conductivity, turbidity, and salinity, were taken using a portable multi parameter water quality meter. Transparency was measured with a Secchi disk. Water samples for nitrates, phosphates, chlorophyll-a (Chl-*a*), and total suspended solids (TSS) measurements were collected using a Van Dorn sampler and transferred into 1 L polyethylene bottles. The samples were then stored in cooler boxes at a temperature of approximately 4ºC pending further analysis in the laboratory. Chemical analyses for dissolved nutrients were carried out using photometric methods according to APHA (2005) standards. Samples for soluble reactive phosphorus (PO_4^{3-}) were filtered using 0.45 mm membrane filters, and the filtrate was analyzed using the molybdate assay method (APHA, 2005). Nitrate (NO^{3-}) analyses were performed using the palintest photometer 7500 bluetooth method. For the determination of Chl-a, water samples were filtered through glass fiber filters and extracted in 90% acetone. Chl-a concentration was measured in a 1 cm length cell at the absorbencies of 665 and 750 nm, respectively, using a spectrophotometer according to Pechar (1987). Total suspended solids (TSS) were determined using the gravimetric method as described by APHA (2005).

The membrane filtration technique was used to determine levels of coliforms. At each station, a sterile water sampling cup was used to collect surface water. Water samples were vacuum-filtered through 47 mm membrane filters with 0.45 mm porosity, trapping coliforms on the filter surface. The filter was then transferred into a petri dish containing an absorbent pad soaked in M-lauryl sulfate broth media and incubated for 24 hours at 37ºC and 44.7ºC for total coliforms and fecal coliforms respectively. Discreet yellow colony-forming units developed after incubation. They were counted manually with the help of the membrane grids for interpretation (US EPA, 2002).

Fisheries

Fish samples were collected using both multi and monofilament gill nets of various mesh sizes ranging from 2 - 4. The nets were set and lifted after 22 hours. Seines were also deployed (set of three seine with 3 hauls of 15 mins. Fish caught by the various nets were removed and sorted. The total length (TL), standard length (SL), and body depth (BD) for each fish caught was measured in millimetres while body weight was measured in grams. All fish samples were dissected and their gonads were examined for sex and maturity stages according to a classification modified by Lagler (1978).

Socio-economic Survey

Data collection was through a mixed sampling approach with structured questionnaires randomly administered to the community living in the vicinity of Lake Elementaita ($n = 50$). Quantitative data was collected on the community's Lake usage, conservation, ecosystem services, livelihoods, governance, and management of the Lake. Other aspects investigated included communication and awareness of management aspects of the Lake. Data on the demographic characteristics of the community was also collected.

Data analyses

Descriptive statistics were used to analyze water quality parameters, including measures of central tendency (means, standard deviations) to summarize key physicochemical variables. Fish size (total length, TL, cm) was analyzed using length-frequency plots to visualize size distribution, while the length-weight relationship was determined using the regression equation by Wootton (1990). The condition factor (K) was calculated using Fulton's formula (Froese, 2006) to assess fish health. For the socioeconomic survey, descriptive statistics such as frequencies and percentages were used to analyze demographic data, ecosystem services provided by Lake Elementaita, major activities around the Lake, and challenges affecting respondents' livelihoods. Responses on proposed measures for Lake conservation and community benefits were categorized into common themes for qualitative insights. All data were entered and processed using Microsoft Excel.

Results and discussion

Ecological Assessment

The average depth of Lake Elementaita was 0.65 m, with the deepest point being at the Midlake section. The Lake exhibited wide temperature ranges, spanning from 21°C to 43°C, with the highest temperatures recorded at the Hotspring point (Table 1).

The mean dissolved oxygen (DO) recorded was 12.99 ± 6.49 mg L^{-1} indicating adequate oxygen saturation to support aquatic life. Total dissolved solids values were high across all sampling stations with a high of 12704.0 ± 5352.53 mg L-1 at Soysambu. This high TDS values in all sites could be associated with high concentrations of dissolved minerals as a result of volcanic activities and high evaporation rates experienced in the Lake (Ondiere, *et al.,* 2017). Electrical conductivity levels were also high with mean value of 15292 ± 7265 µS cm^{-1} (Table 1). These recorded values are lower than values (39000 µS cm^{-1}) recorded by Odour and Schagerl (2007) and 61500 µS cm^{-1} Njenga (2004). This variation could be attributed to the dilution effect of the recent lake level rise of Rift Valley lakes. Heavy rainfall can also lead to runoff from surrounding land, carrying sediment, organic matter, and nutrients into the lake.

High levels of chlorophyll-a (Chl-a) concentrations were observed in Lake Elementaita, with mean values of 33.48 ± 13.01µg L^{-1}, indicating significant algal biomass in the Lake (Table 2). This is supported by the observed large number of lesser flamingo that feed on the *Spirulina*. Various factors, including nutrient availability, temperature, light availability, and water column stability could also contribute to the high concentrations (Schagerl *et al.*, 2015). The mean concentration of total suspended solids was 190.81 ± 90.76. These levels are above the permissible limits of the United States Environmental Protection Agency (US EPA) of < 30 mg L^{-1}.

Table 1. Physicochemical variables in Lake Elementaita. (Temp -Temperature; EC- Electrical conductivity; DO- Dissolved oxygen; TDS-Total dissolved solids; ORP- Oxidative reduction potential; SD - standard deviation) during sampling period.

Site	Depth (m)	Temp. °C	EC (µS/cm)	DO (mg/L)	pH	TDS (mg/L)	Salinity (ppt)	Turbidity (mg/L)	Secchi depth (cm)	Pressure (mm/Hg)	ORP (mv)
Pelican	0.7	25.35	18955.00	16.9	9.5	12216.8	11.1	317	8.0	594.5	47.3
Sentrim	1.0	23.50	18345.00	16.9	9.8	12232.5	11.2	276	7.25	594.5	32.4
Mbaruk RM	0.9	28.10	19645.00	19.6	10.0	12028.0	11.9	308	7.5	593.3	31.4
Flamingo Island	0.7	25.10	19290.00	16.6	9.9	12525.0	11.4	298	13.5	593.0	36.0
Midlake	1.2	21.85	17915.00	7.6	10.0	12398.8	11.4	276	10.0	592.7	44.8
Soysambu	1.0	21.40	18245.00	11.6	9.7	12704.0	11.6	286	9.0	595.5	27.2
Hotspring	0.07	43.10	4770.00	2.6	9.5	23.0	1.8	1.7	-	595.1	14.1
Off Hotspring	0.49	28.50	19910.00	20.0	9.9	12122.5	11.0	303	7.6	594.5	37.0
Kariandusi RM	0.01	26.30	560.00	5.2	8.3	357.5	0.3	38.7	-	593.9	82.9
MEAN	0.65	27.02	15292.78	12.99	9.60	9623.11	9.07	233.82	8.97	594.09	39.23
SD (±)	0.39	6.52	7265.86	6.49	0.53	5352.53	4.58	122.25	2.22	0.96	19.05

Table 2. Mean values of Chl-*a*-Chlorophyll-*a* (µg L-1) and TSS - Total suspended solids (mg L-1).

Site	Chl-*a* (µg L-1)	TSS (mg L-1)
Pelican	41.4	238
Sentrim	37.5	248
Mbaruk RM	37.8	242
Midlake	37.6	160
Soysambu	38.8	241
Hotspring	3.5	23.5
Kariandusi RM	27.5	92
Off Hotspring	43.9	282
Flamingo Island	-	250
Mean	33.48	190.81
SD (±)	13.01	90.76

Results of nitrates during the sampling period was 0.03 mg L^{-1}, suggesting a relatively low input of nitrogen-containing compounds into the lake (Table 3). Nitrogen is an essential nutrient for phytoplankton growth, and its availability can influence Chl-a concentrations and overall ecosystem productivity. The limited nitrate input may indicate a lower potential for nitrogen-driven eutrophication compared to lakes with higher nitrate levels. On the other hand, the average phosphate concentration was 0.09 ± 0.05 mg L^{-1} (Table 3). These values are lower compared to historical values recorded by Oduor and Schagerl (2007). The decrease in nitrates and phosphate concentrations compared to previous studies could be as a result of the existing management measures by Kenya Wildlife Service to ensure there are no human activities around the park.

Low phosphate levels are often desirable because they can help mitigate the risk of eutrophication, and excessive growth of algae and aquatic plants due to high nutrient levels. Studies by Adeka *et al.*, (2008) indicated that the hot spring is a major source of dissolved nitrogen, dissolved phosphorus, and total phosphorus in Lake Elementaita.

Table 3. Mean values of Nutrients Nitrates (NO^3); Soluble Reactive Phosphates (SRP).

Site	NO^{3-} (mg L-1)	SRP (mg L-1)
Pelican	0.05	0.12
Sentrim	0.03	0.11
Mbaruk RM	0.01	0.11
Midlake	0.04	0.14
Soysambu	0.05	0.09
Hotspring	0.01	0.03
Kariandusi RM	0.03	0.00
Off Hotspring	0.01	0.09
Flamingo Island	0.02	0.15
Mean	0.03	0.09
SD (±)	0.02	0.05

Total and fecal coliforms were observed in majority of the sampling points excluding Hotspring and Soysambu points, indicating a widespread distribution of these bacteria throughout the Lake (Table 4).

Table 4. Coliform forming units (cfu) of total and fecal coliforms in Lake Elementaita."-": not detected; tntc: too numerous to count.

Sampling point	Total Coli (cfu 100 ml-1)	Fecal coliforms (cfu 100 ml-1)
Midlake	100	-
Pelican	tntc	1333
Sentrim	40	40
Hotspring	-	-
Soysambu	-	-
Kariandusi R.M	-	-
Island	tntc	333
Mbaruk R.M	367	-

The areas where coliforms were observed are characterized by large populations of flamingoes and pelicans, which are known to inhabit shallow, nutrient-rich waters, which provide the ideal conditions for the proliferation of coliforms. Other factors such as agricultural runoff,and wildlife activities could contribute to the values recorded above. It's important to note that the presence of fecal coliforms in water poses a potential health risks to humans.

Fisheries

During the period of this study, only Magadi tilapia *(Alcolapia grahami)* fish species was caught with a total wet weight of 14 kg. The catch rates of this species was 0.4 kg hr^{-1} and 1.4 kg hr^{-1} using gill netting and seining respectively, yielding an average catch rate of 0.9 kg hr^{-1}. *A. grahami* is tolerant to very alkaline conditions (Maina *et al*., 2019), contributing to its abundance in Lake Elementaita. The alkaline nature of the lake influences habitat availability, food resources, and interspecific interactions, shaping the population dynamics of *A. grahami* within the ecosystem. The species' ability to thrive in such environments underscores its ecological resilience and evolutionary adaptations.

Analysis of mean length, weight, and condition factor provided valuable insights into the status and general well-being of *A. grahami* populations in Lake Elementaita (Table 5). The mean sizes and condition factor of this species in Lake Elementaita may indicate a relatively stable population structure, suggesting favourable environmental conditions and resource availability. However, variations in condition factors could be attributed to seasonal changes in food availability, environmental quality, and reproductive dynamics (Yongo *et al*., 2019).

Table 5. Morphometric parameters and condition factor of *A.grahami* in Lake Elementaita

Measure	Sample size	Range (cm)	Mean size (±SD)
Length	244	5 to 13	8.55 ± 1.55
Weight	244	2 to 48	13.03 ± 7.56
Condition factor (K)	244	0.02 to 2.73	1.78 ± 0.45

The length-frequency data for *A. grahami* revealed that most of the fish measured between 9 cm and 10 cm in total length(Fig. 2). These values recorded are slightly higher than those recorded in Lake Magadi by Maina *et al.,* (2019). However, total length of 20.0 cm have been recorded (Froese and Pauly, 2017).

Length weight relationship analysis of the combined sex revealed that *A. grahami* showed a positive allometric growth for width b = 3.1 implying that the fish increased its weight faster than its length.

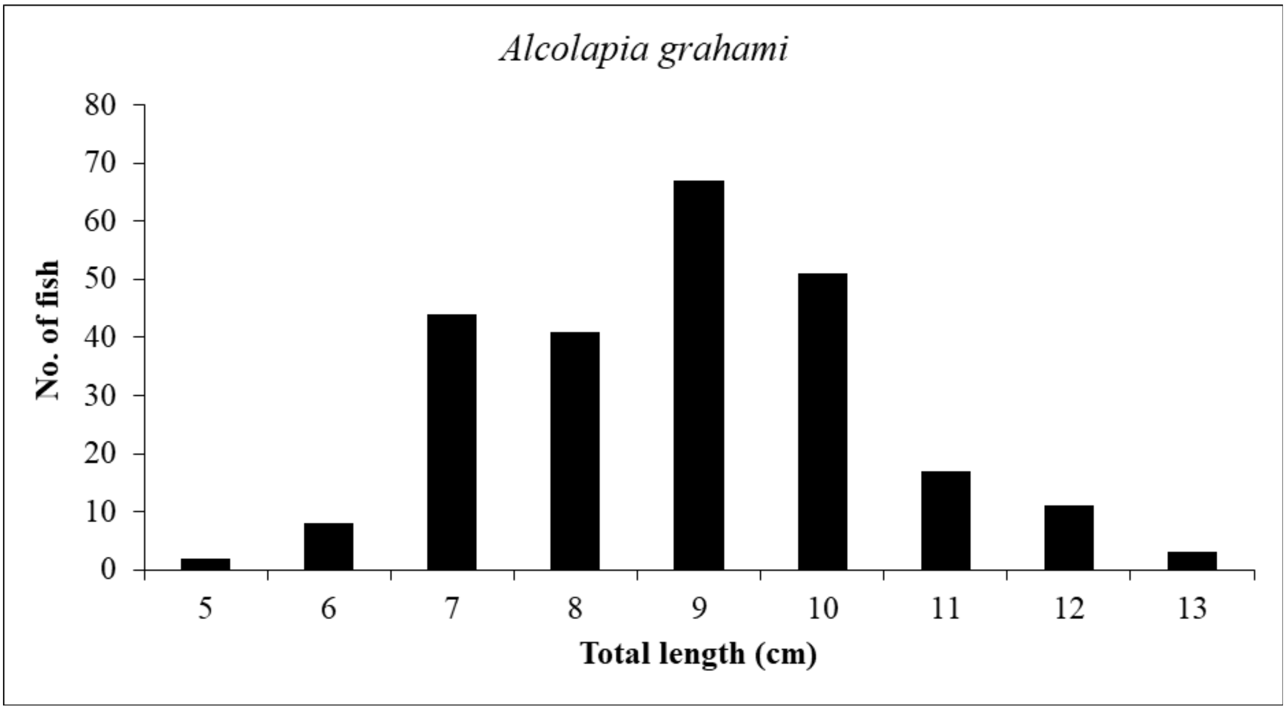


Figure 2. Length frequency structure of *A. grahami* in Lake Elementaita.

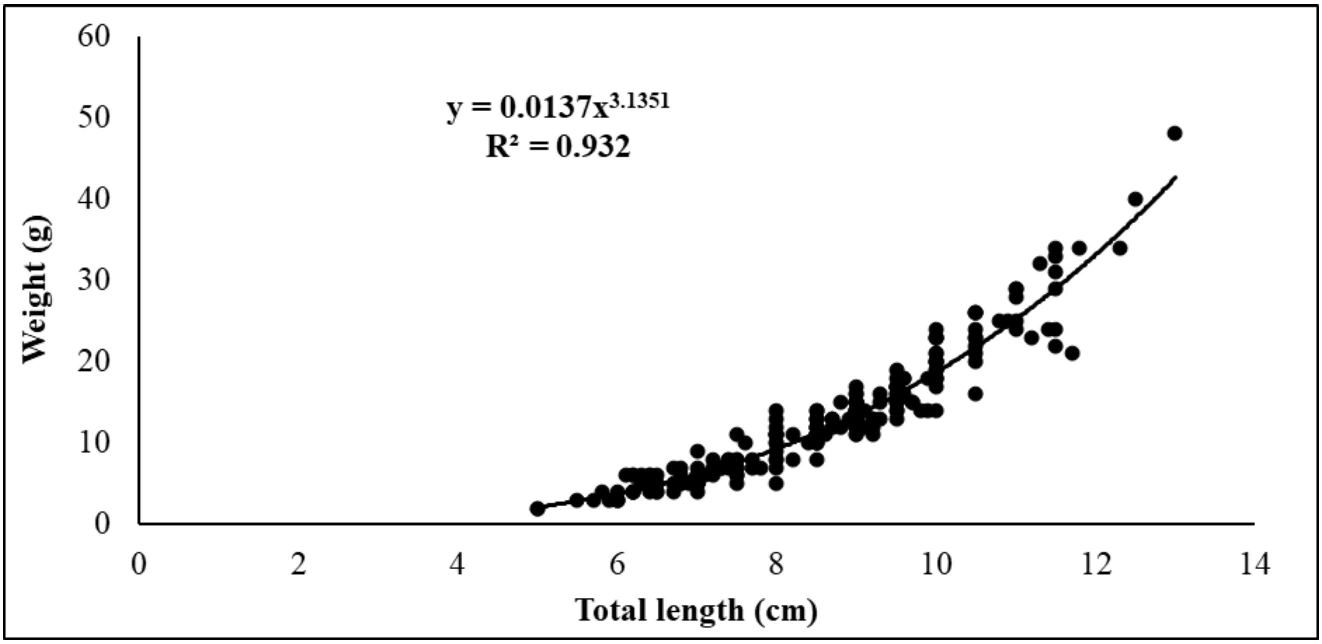


Figure 3. Length-weight relationship of *A. grahami* in Lake Elementaita.

(Fig. 3). Change of b values depends primarily on the shape and fatness of the fish species as well as physical, chemical, and biological factors such as temperature, salinity, food, stomach fullness, sex, and stage of maturity (Sparre and Venema, 1998; Sarkar *et al.,* 2013).

Sex ratio composition of the total catch comprised of 52% males, and 48% females (0.92:1) (Fig. 4), with a large proportion of this catch (80% of females and 89.8% of males) being mature. These results suggest a relatively balanced sex distribution within the fish population, indicating a stable self-replenishing stock.

Socio-economic survey

Sixty-four (64%) of the respondents in the study were male aged between 21 and 30, constituting the majority of the respondents. Other demographic characteristics are as shown in table 6.

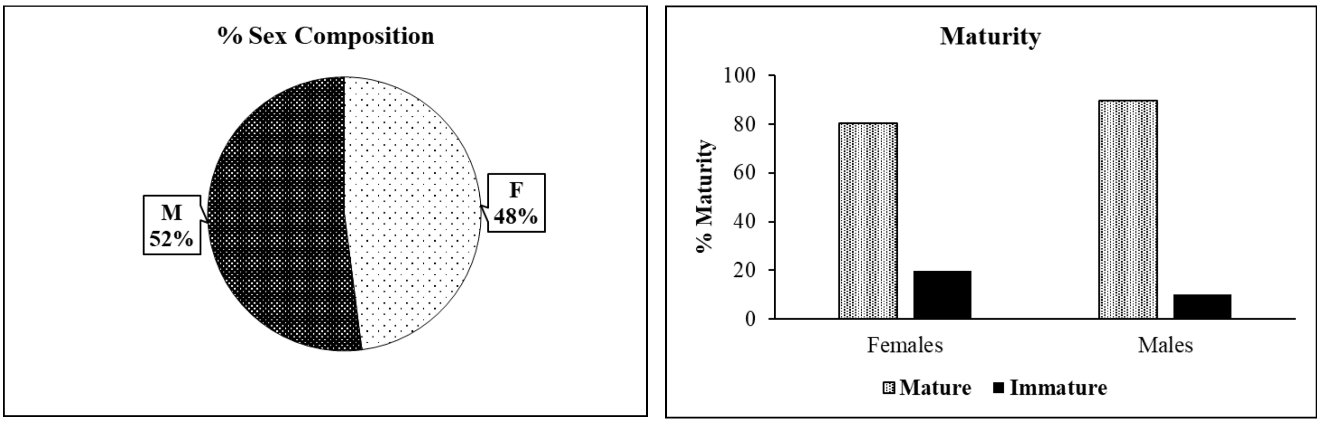


Figure 4. Percentage sex composition and maturity of *A. grahami* in Lake Elementaita.

Table 6. Summary of demographic data from the respondents.

Characteristics		N	Proportion (%)
	Female	18	36
Gender	Male	32	64
	n	50	100
	<20	11	22
	>50	4	8
Age	21_30	19	38
	31_40	11	22
	41_50	4	8
	N/A	1	2
	n	50	100
	Primary	9	18
	Secondary	30	60
Education level	Vocational training	6	12
	Degree	5	10
	n	50	100
	Divorced	1	2
	Married	20	40
Marital status	N/A	4	8
	Single	22	44
	Widow	2	4
	Widower	1	2
	n	50	100
	Students	10	20
	Self-employed/Business	9	18
	Employed	6	12
Occupation	Hustler	6	12
	Farmer	5	10
	N/A	14	28
	n	50	100

Survey findings point to a robust recognition among respondents of the ecosystem services provided by Lake Elementaita, with recreation and tourism emerging as the most prominently acknowledged ecosystem service that the community identify, with 67.1% of primary benefit. The Lake's scenic beauty, wildlife viewing opportunities, and cultural significance make it a popular destination for recreational activities and ecotourism ventures.

Furthermore, respondents also highlighted the importance of biodiversity conservation and ecological balance, recognizing the Lake's role in supporting diverse flora and fauna and maintaining a healthy ecosystem dynamic. Additionally, climate regulation was acknowledged as a critical service provided by Lake Elementaita, with respondents recognizing its role in moderating local climate conditions and mitigating the impacts of climate change. Table 7 outlines more services as cited by the respondents.

Table 7. Ecosystem services the Lake provides to the community.

Service	No. of respondents	Proportion (%)
Recreation and tourism	47	67.1
Biodiversity and ecological balance	10	14.3
Climate regulation	10	14.3
Fisheries and food resources	2	2.9
Freshwater for drinking and irrigation	0	0.0
Treatment of skin ailments	1	1.4
n	70	100.0

From the study, a significant proportion of respondents frequent Lake Elementaita weekly, with individuals citing engaging in various activities such as bird watching (49%) and tourism (25%). Other activities carried out around the lake are shown in figure 5.

Some of the challenges faced by the community members living near the Lake as cited by the respondents included park entry restrictions (28.3%), water pollution (21%), human wildlife conflict (13.3%)(Table 8).

Table 8. Major challenges related to the Lake that affect respondents' livelihoods.

Challenges	Respondents (%)
Restricted entry	28.3
N/A	25.0
Water pollution	21.7
Human-wildlife conflict	13.3
Encroachment	5.0
Mosquitoes infestation	3.3
Migration of birds	1.7
An increase in lake levels causes floods	1.7
Total	100

Some of the threats facing lake Elementaita based on the perceptions of the community are climate change (21%), pollution (19%), and deforestation (16%). These were deemed as urgent, requiring immediate interventions. To conserve the Lake Elementaita ecosystem, and based on the foregoing results, the community reported having engaged in interventions such as tree planting (30%), undertaking clean ups (25%), community awareness and patrols (10%), while the majority (35%) of the respondents were not cognizant of any community interventions.

On Lake Elementaita governance, resource and other legal frameworks, the study established that 60% of the respondents were familiar with

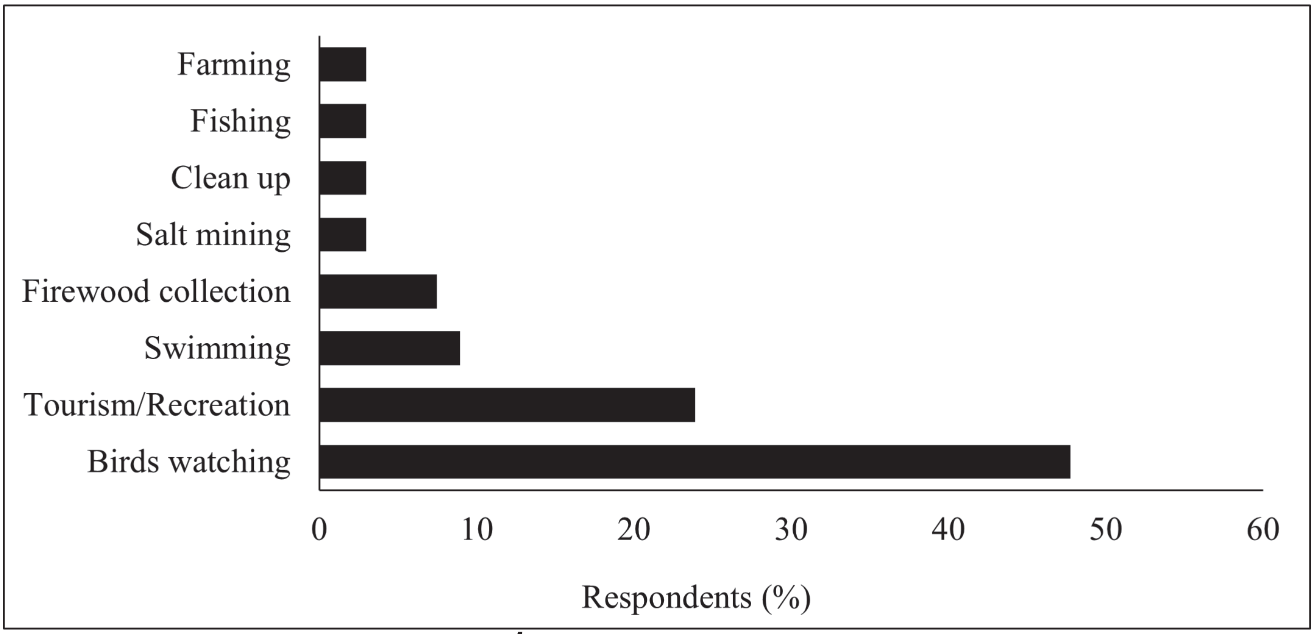


Figure 5. Major activities undertaken/ observed around Lake Elementaita.

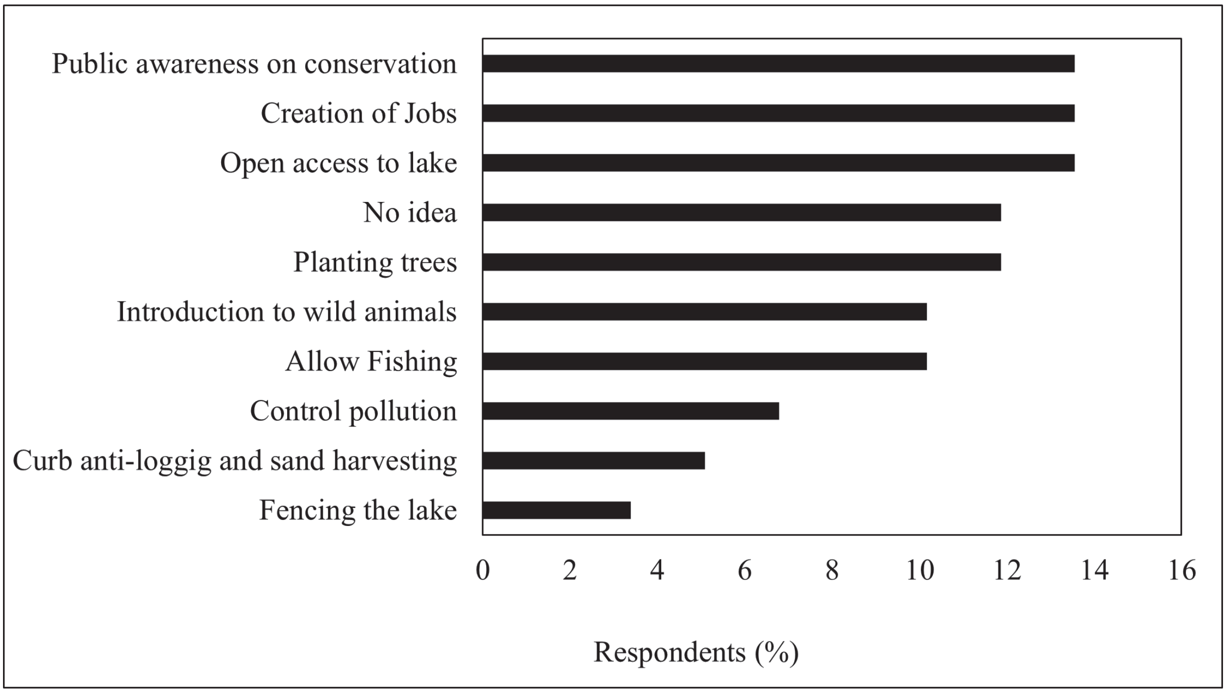


Figure 6. Measures to be implemented to improve the Lake's condition and benefit the local communities.

regulations and policies governing the use of the resource, indicating a relatively high level of awareness among the local population regarding the legal framework guiding Lake management and conservation efforts. However, 40% of respondents lacked awareness of any existing regulations, suggesting the need for community sensitization on the role of government agencies in resource conservation and management. The most cited legislation included restricted entry and access, anti-poaching, restrictions on water abstraction, restriction on fishing activities, and pollution control.

Several recommendations were proposed from this study, notably, allowing the Lake to be an open access system, exploring opportunities for income generation activities for instance ecotourism, and other recreational activities, public awareness campaigns, and encouraging tree planting (Fig. 6).

Conclusions and recommendations

Lake Elementaita exhibits considerable physicochemical variability, with wide temperature fluctuations, sufficient dissolved oxygen levels, and high total dissolved solids (TDS) concentrations. Elevated chlorophyll-a levels indicate significant algal biomass, likely driven by nutrient availability and environmental factors. *Alcolapia grahami* was the only recorded fish species, with a stable and well-adapted population. The local communities demonstrated a strong dependence on the lake for vital ecosystem services, including biodiversity conservation, tourism, and climate regulation. These findings highlight the need for integrated watershed management and targeted conservation strategies to safeguard Lake Elementaita's ecological integrity and sustain its socio-economic benefits. This includes implementing soil conservation measures, establishing riparian buffer zones, and promoting sustainable agricultural practices to minimize nutrient and sediment runoff. Additionally, enforcing existing regulations on lake use, such as entry restrictions and pollution control measures, is crucial for mitigating human-induced pressures.

Acknowledgement

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Assessment of the plastic pollution levels along Ferguson's Gulf, Lake Turkana

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Abstract

Plastic pollution is the accumulation of plastic objects and particles in the environment that has an adverse effect on humans, wildlife and their habitats. The present study aimed at assessing the level of plastic pollution along Ferguson's Gulf in Lake Turkana. Five sampling sites, namely Daraja, Namakat, Namkuse, Kenya Oil and Longe'ch were selected. Random sampling was done using 100 m^2 quadrats to quantify and identify the plastic debris that occur at the sites due to human settlement, fishing and other anthropogenic activities. Results showed that Daraja had the highest proportion of plastics at 28%, while Namkuse was least affected at 6%. With plastics categorized as polyethylene terephthalate (PETE), high density polyethylene (HDPE), polyvinyl chloride (PVC or Vinyl), low density polyethylene (LDPE), polypropylene (PP), polystyrene (PS or Styrofoam) and others, PETE was the most abundant at 45% while PS and PVC was the least abundant (3%). Higher plastic density (2 debris m^{-2}) was observed in Daraja and Namakat compared to Kenya Oil and Longe'ch (1 plastic debris m^{-2}). Daraja was therefore considered a plastic pollution hotspot in comparison to the rest of the sites. Recommendations proposed include the provision of waste bins, capacity building or sensitization forums on the negative impacts of plastic pollution and enforcement of relevant regulations by the National Environment Management Authority (NEMA). Otherwise, plastic pollution could adversely impact aquatic life inhabiting Ferguson's Gulf.

Keywords: plastic pollution, anthropogenic, debris, Ferguson's Gulf, Lake Turkana

Introduction

The accumulation of plastic objects and particles (e.g., plastic bottles, bags and microbeads) in the environment that adversely affects humans, wildlife and their habitat is considered plastic pollution (Carpenter *et al.,* 1972). Plastic pollution is ubiquitous, from deserts to farms, from mountain tops to the deep ocean, in Arctic snow and in tropical landfills (Borrelle *et al.,* 2020). Reports of plastic debris in the marine environment date back to half a century ago (Carpenter *et al.,* 1972). A number of reports indicate that plastic pollution poses significant threats on aquatic life, ecosystems, and human health (Derraik, 2002; Rochman *et al.,* 2015; Conchubhair *et al.,* 2019). It is estimated that 9.2 billion tonnes of plastic were produced between 1950 and 2017 (Borrelle *et al.,* 2020), with more than half this volume having been produced from 2004.

Plastics pollutants are categorized by size as micro-, meso-, or macro- debris (Borrelle *et al.,* 2020). Within these three categories, there are seven main types of plastics viz., polyethylene terephthalate (PET or PETE), high density polyethylene (HDPE), polyvinyl chloride (PVC or Vinyl), low density polyethylene (LDPE), polypropylene (PP), polystyrene (PS or Styrofoam) and other types of plastic . Plastics are inexpensive and durable, making them very adaptable for different uses, thus, manufacturers choose to use plastic over other materials. However, the chemical structure of most plastics renders them resistant to many natural processes of degradation and as a result they are slow to degrade (Lau *et al.,* 2020). These two major factors contribute to the accumulation of large volumes of plastic in environment as mismanaged waste and the subsequent long-term persistence of plastic debris in the environment.

It is reported that plastic pollution is on an increasing trend and will continue to increase, even in some of the most optimistic future scenarios of plastic waste reduction (Borelle *et al.,* 2020). Estimates of global emissions of plastic waste to rivers, lakes, and the ocean range from 9 to 23 million mt year^{-1}, with a similar amount emitted into the terrestrial environment, ranging from 13 to 25 million mt year^{-1} as of 2016 (Borelle *et al.,* 2020). According to Geyer et al. (2017), only 9% of all plastics ever made are recycled. Plastic pollution occurs as accumulated waste, accumulated marine litter, fragments or microparticles of plastics and non-biodegradable fishing nets which continue to trap wildlife, causing the death of animals by ingestion of plastic objects and finally, the introduction of microplastics and microbeads of plastics from cosmetic and body care products (Borelle *et al.,* 2020).

Plastics contribute to approximately 10% of discarded waste. Many kinds of plastics exist depending on their precursors and the method for their polymerization. Depending on their chemical composition, plastics and resins have varying properties related to contaminant absorption and adsorption. Polymer degradation takes much longer as a result of saline environments and the cooling effect of the sea, factors that contribute to the persistence of plastic debris in certain environments (Barnes *et al.,* 1998). However, The Environmental Report (UNEP, 2021) indicated that plastics in the ocean decompose faster than was once thought, due to exposure to sun, rain, and other environmental conditions, resulting in the release of toxic chemicals such as bisphenol. It is estimated that a foam plastic cup takes 50 years, a plastic beverage holder takes 400 years, a disposable nappy takes 450 years, and a fishing line takes 600 years to degrade.

Of all the plastic discarded so far, 14% has been incinerated and less than 10% has been recycled (Barnes, 1998). In Lake Turkana, especially along the Ferguson's Gulf, there are a number of activities that involve the purchase and use of plastic products in the informal settlements. A number of small and micro enterprise activities serve the fisher communities inhabiting the area around the Gulf. These enterprises sell products that involve use of plastics or are plastic in nature. Water containers, sweet rappers and cold drink bottles are some common types the plastic waste generated from these products. Fishing gear, especially monofilament nets are also discarded everywhere. The scarcity of portable water has further exacerbated the situation, with most portable water containers being plastic. These factors contribute significantly to plastic pollution and hence the need to assess the level of their pollution in the study area.

The main objective of the present study was to assess the level of plastic pollution along the Ferguson's Gulf in Lake Turkana to provide information for sustainable management of the area. Specifically, the study intended:

i. to assess the major types of plastic pollution along Ferguson's Gulf;
ii. to quantify plastic pollutants along Ferguson's Gulf;
iii. to identify major plastic pollution hotspots along Ferguson's Gulf; and
iv. to determine the intensity of plastic pollution along Ferguson's Gulf.

Materials and methods

Study area

Lake Turkana, lies within the Great Rift Valley in Northern Kenya. The Lake is approximately 250 km long, with an elevation of about 360 m above sea level and a maximum depth of 120 m. It has a surface area of 7,500 km^2, making it the largest lake in Kenya. Ferguson's Gulf lies 3°30′ 51″ N, 35°0 54′ 58″ E within the mid-Western part of Lake Turkana. Its surface area fluctuates depending on Lake levels at any given time (Kolding, 1989). It is a major fishing ground and is completely surrounded by informal settlements where various activities, including small and medium enterprises are undertaken (Kolding, 1989).

In the current study, five sites were identified for sampling of plastic pollutants, i.e., Daraja, Namakat Namkuse, Kenya Oil, and Longe'ch. The five sites were situated in settlement areas with fishing activities being undertakes at the shore. Shopping stalls and kiosks for refreshments characterize the area. Entertainment joints like bars and whisky shops are available as well. All these activities use plastics containers in one way or another to sell the products.

The five sites were located at different points along the Ferguson's Gulf of Lake Turkana. Amenities like schools and churches were found in the vicinity of the Gulf and one ice making enterprise (Adili Hub Ltd) was operating at the vicinity of Longe'ch as a source for ice.

Data collection and analysis

Random sampling using a 10 m x 10 m (100 m^2) quadrat was done to quantify and identify the types of plastic in the selected sites. Each site was randomly sampled in triplicate by marking the quadrat area and collecting all types of plastic within the quadrats. The samples were placed in gunny bags and sorted according to the seven types of plastics as per the identification chart developed (Table 1).

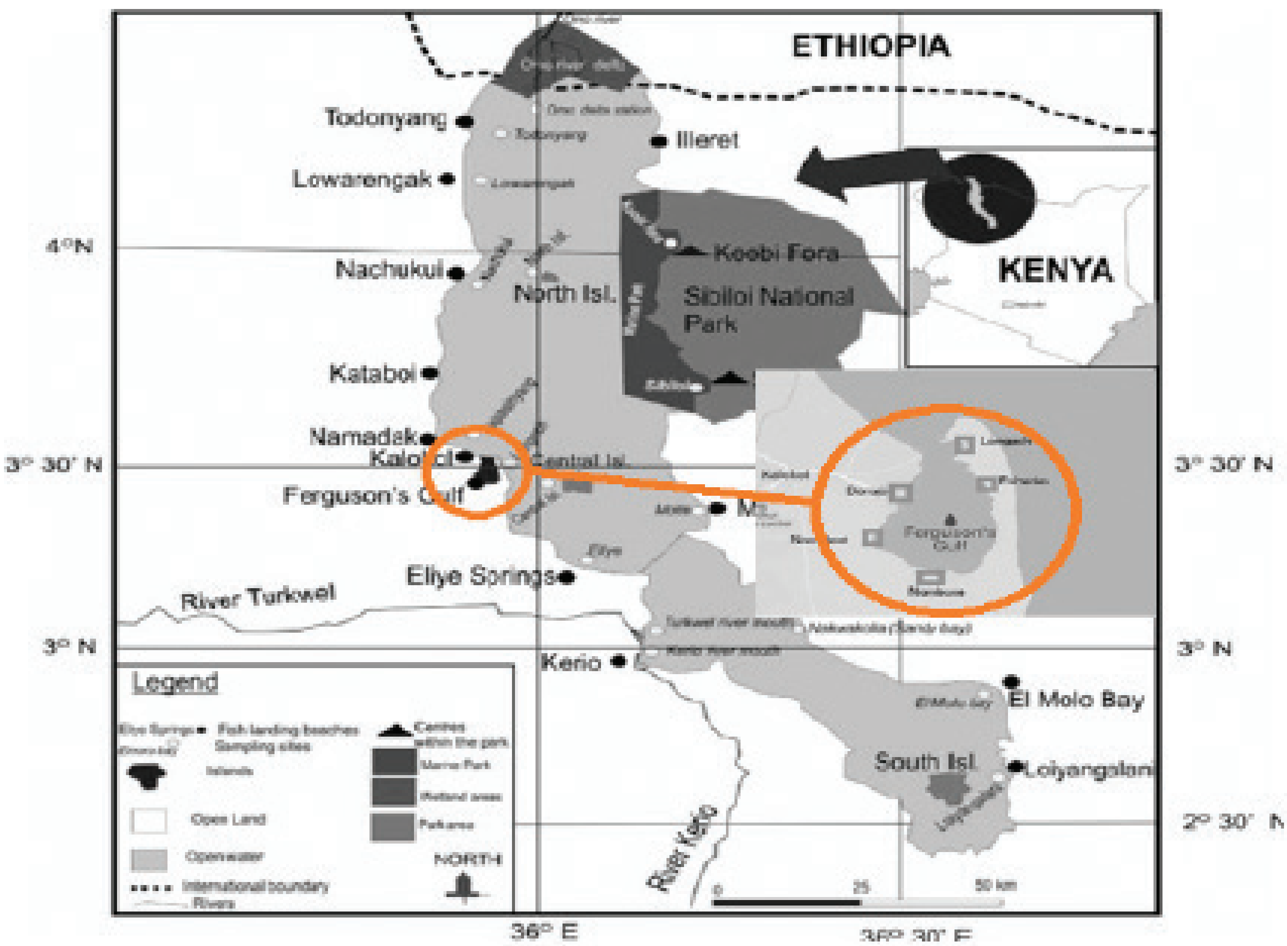

Figure 1. Map of Lake Turkana showing the study area (Source: Authors).

Table 1. Identification chart developed to characterize the samples collected based on the type of plastic.

Type of plastic	Sample type
Polyethylene terephthalate (PET or PETE)	Included soft drink bottles, drinking water bottles and cooking oil containers
High density polyethylene (HDPE)	Included milk jugs, laundry detergent bottles, cleaning solution bottles, shampoo bottles and conditioner bottles
Polyvinyl chloride (PVC or Vinyl)	Included cling wrap and piping (for plumbing)
Low Density Polyethylene (LDPE)	Included shopping bags and squeeze bottles
Polypropylene (PP)	Included drinking straws, medicine bottles and condiment bottles
Polystyrene (PS or Styrofoam)	Included clam-shell take out packaging and Styrofoam plastics
Other plastic forms	All other types of plastic waste

For each quadrat, the data were inserted in a pre-designed form, capturing the sample type and respective type of plastic collected at each of the five sampling sites. The data was subsequently entered Ms Excel spreadsheets and analyzed using the same application. Descriptive statistical analysis was done and the results mainly presented in graphs, tables and pie charts.

Results and discussion

Major types of plastic pollution

The major plastic type observed in the sampling sites was PETE, consisting of drinking bottles, bottled water containers and cooking oil bottles, totaling to 892 pieces (Table 2). Hot weather encourages use of drinking water in plenty, including use of juice and other food stuffs packaged in plastic containers. Most of the kiosks and shops store a lot of drinks and water bottles which are used and then scattered everywhere because there are no waste disposal bins or designated wastes disposal sites.

The second most abundant plastic type was LDPE, consisting of shopping bags and squeeze bottles. Shopping bags present a significant environmental concern owing the comparatively high frequency of utilization for shopping activities. The bags are predominantly single-use and rarely reused, resulting in their high accumulation as pollutants as a result of poor waste management practices.

The third category of plastics observed was the type of plastics categorized as other types, consisting mainly of monofilament nets dumped by the shore. The plastics pose a great danger to aquatic life, especially through ghost fishing and ingestion of microplastics. This is due to the disposal of fishing nets are at the beach, without any regard to the potential impacts on biodiversity. Limited access to portable water also contributes significantly to the use of drinking water packaged in plastic bottles, which further contributes to the rampant pollution in the study area.

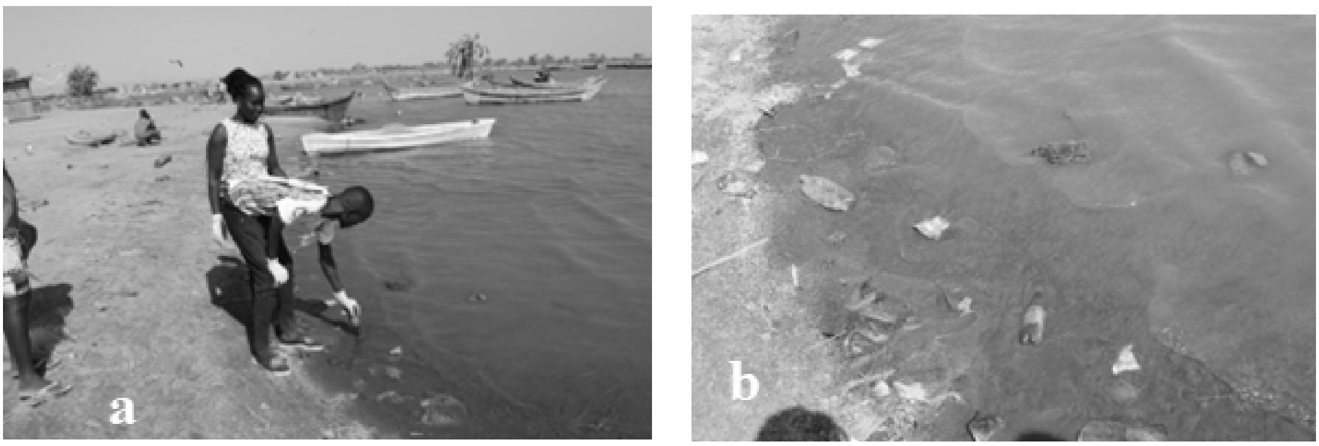

Figure 2. Plastic waste accumulation at the land-water interface along Ferguson's Gulf (Source: Authors)**.**

Table 2. Number of plastic types at various sampling sites along Ferguson's Gulf in Lake Turkana. PETE: polyethylene terephthalate, HDPE: high density polyethylene, PVC: polyvinyl chloride, LDPE: low density polyethylene, PP: polypropylene, PS: polystyrene (styrofoam).

	Daraja	Namakat	Namkuse	Kenya Oil	Longe'ch	Total
PETE	346	224	58	152	112	892
HDPE	16	36	21	43	5	121
PVC	2	3	15	22	11	53
LDPE	51	22	23	217	192	505
PP	64	39	1	3	1	108
PS	26	29	0	1	6	62
Other types of plastics	47	101	13	12	64	237
Total	552	454	131	450	391	1978
% Composition	28	23	6	23	20	100

The least amongst the plastic types was the PVC. This was attributed to the fact that piping has not been scaled up in the study area, as evidenced by limited water pipes and lack of houses with piped water. Each sampling site exhibited unique plastic type composition determined by the activities being practiced therein.

Daraja site

Results showed that Daraja had the highest plastic composition out of the five sampling sites at 28% (Table 2). This could be attributed to the lack of portable water in Daraja. Majority of the residents prefer using bottled drinking water since water sourced from the Lake is mainly used for cooking and household chores. This contributes highly to plastic pollution in the site. Another source of plastic pollutants are the cooking oil containers. Deep frying is a major fish processing method in this area. The cooking oil used for this method of fish processing is sold in plastic containers, some of which are not recycled. The plastic waste is littered everywhere causing major plastic pollution in the area. Other major sources are travelers and traders who use plastic containers for either selling their products or purchase products packaged in plastic. Some of these containers are left to litter in the area, contributing to high plastic pollution. Fresh fruits and vegetables are wrapped in plastic bags which are also discarded anywhere in the area after use. Environmental factors, such as strong winds, facilitate the dispersal of accumulated litter from the lake shore throughout the study area. The confluence of these anthropogenic activities and inadequate solid waste management infrastructure has rendered Daraja a critical hotspot for plastic pollution within the Gulf region.

Namakat site

Namakat recorded the second highest proportion of plastic pollutants, accounting for 23% of the plastics samples collected. The site also recorded a comparatively higher number of PETE plastic types. This was attributed to lack of portable water, necessitating the purchase of bottled drinking water. The hot weather in the region further increases the consumption rate of drinking water.

Kenya Oil site

This sampling site contributed 23% of the plastics sampled. Unlike Daraja, where PETE was the dominant type of plastic, Kenya Oil was dominated by LDPE pollutants, indicating high usage of shopping bags and squeeze bottles.

Longe'ch site

Longe'ch sampling site accounted for 20% plastic samples collected. Similar to Kenya Oil site, shopping bags and squeeze bottles were higher in number than the other plastic types, thus LDPE plastic was the major pollutant at this site.

Namkuse

This site had a unique characteristic in terms of plastic pollution, contributing only 6% of the plastics sampled. All plastic types were few in comparison to other sampled sites, a factor that could be attributed to the low population level in the area. The community in the area has settled in farther away from the beach, resulting in reduced use of plastics at the shore.

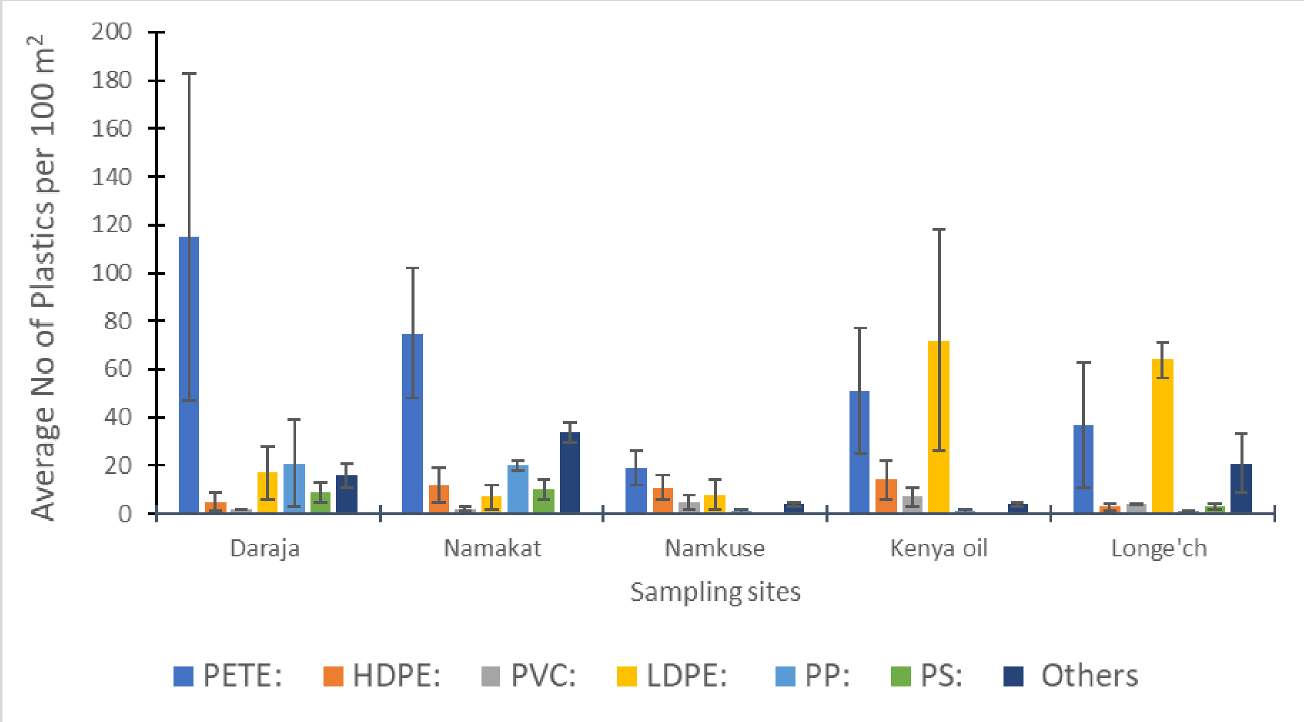

Figure 3. Average number of plastic types per quadrat in various sites along Ferguson's Gulf, Lake Turkana.

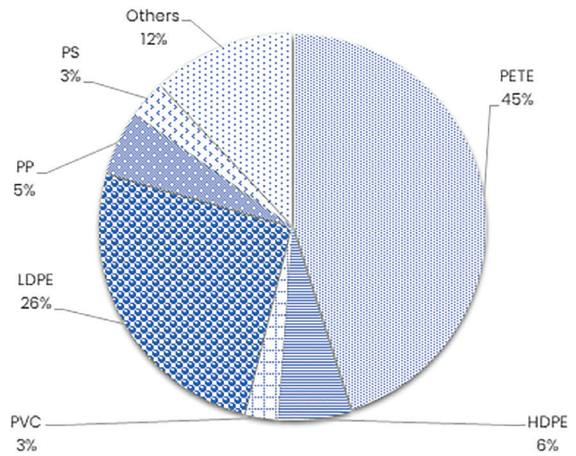

Figure 4. Percentage composition of different plastic along the Ferguson's Gulf, Lake Turkana. PETE: polyethylene terephthalate, HDPE: high density polyethylene, PVC: polyvinyl chloride, LDPE: low density polyethylene, PP: polypropylene, PS: polystyrene (styrofoam).

The results in Figure 4 show the average quantity of plastics in each quadrat in various sampling sites. Daraja sampling exhibited an average value of 115 ± 68 plastics for PETE with the rest of plastic types indicating values below 25 pieces. However, the variation in the number of plastic pollutants in collected in each quadrat was high meaning that different parts of Daraja had significantly different plastic quantity within the same site. It was also noted that Daraja leads in all sampling sites in the quantity of PETE plastic type followed by Namakat (75 ± 27) and Kenya Oil (51 ± 26) respectively. However, Kenya Oil took lead in low-density polyethylene (72 ± 46) followed by Longe'ch (64 ± 7) and Daraja (17 ± 11), respectively.

Relative composition of plastic types along Ferguson's Gulf, Lake Turkana

Results illustrated in Figure 5 indicate that 45% of plastic pollution in the Ferguson's Gulf is caused by PETE plastic type. This was followed by LDPE at 26%. The least type of plastic pollutant in the Gulf is PVC and PS, with a composition of only 3% respectively. Use of bottled drinks, water bottle and cooking oil with no major management of the same therefore pause a major threat to this environment especially to aquatic resources (fish and other aquatic animals) in the Gulf.

The need for waste management through a centralized disposal site and creation of awareness on proper handling of plastic waste is are highly recommended as immediate interventions to reduce the scale of plastic pollution. As shown in Figure 5d, the plastic further dispersed by wind and accumulate next to the shore posing a significant threat to water quality and ultimately to aquatic life.

Figure 5. Some of the plastic waste at Daraja landing site (Natirae BMU) along Ferguson's Gulf, Lake Turkana (Source: Authors)**.**

Discarded fishing gear should to be removed from the water and away from the shore for proper disposal. Beach Management Units (BMUs), the fisher community and other stakeholders require to be responsive to this problem and come up with effective ways to deal with it for sustainable management towards a clean and healthy environment.

Pollution hotspots in Ferguson's Gulf

The results show that Daraja is the most affected site in terms of plastic pollution (Fig. 7). This could be attributed to its proximity with Kalokol, a major shopping center with a comparatively high population. Most of the people operating at Daraja live in Kalokol and contribute to the introduction of plastic in form of shopping

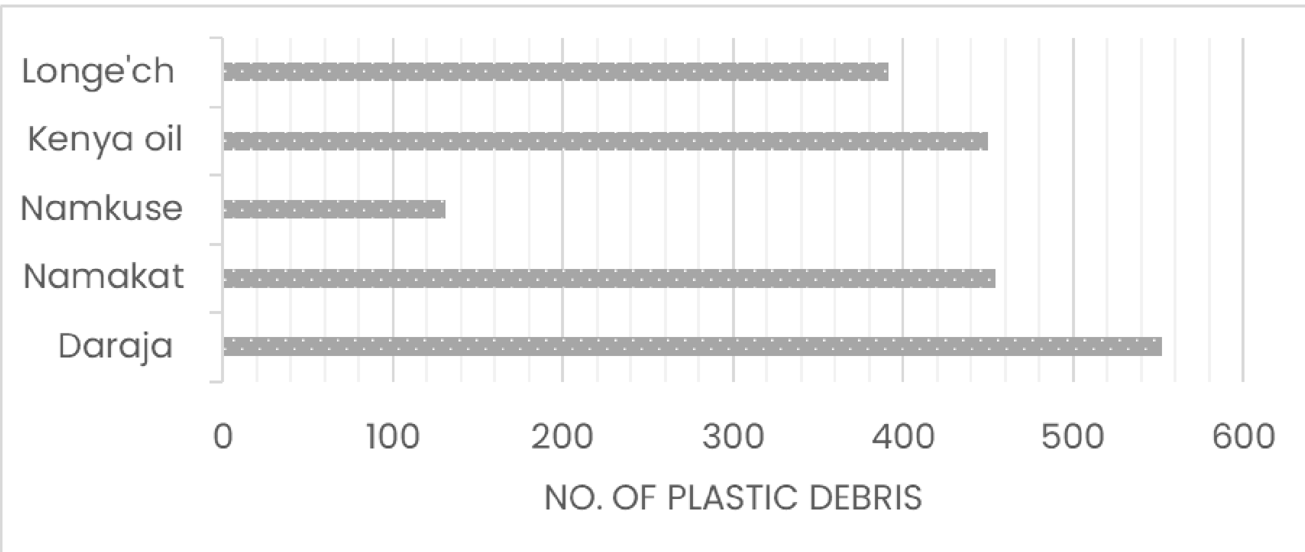

Figure 6. Number of plastic debris collected at different sampling sites along Ferguson's Gulf, Lake Turkana.

bags, drinking water bottles and oil containers to the site. Most these single-use plastic containers are dumped at the site, ultimately leading to high plastic waste at the beach. Secondly, Daraja is easily accessible by visitors and frequent traders from other locations who purchase fish while on transit to distant markets. Most of these visitors carry drinking water and other bottled drinks for use at the beach. These factors make Daraja site a hotspot in terms of plastic pollution.

Daraja site is closely followed by Namakat and Kenya Oil respectively. Owing to the gradual increase in the water levels of Lake Turkana, people inhabiting the Gulf have been relocating to settle in higher ground. This has resulted in an increase in the population of Namakat and Kenya Oil, which has contributed to a the increased use of plastic products such as shopping bags and consumables packaged using plastic containers such as cooking oil, bottled drinks and drinking water. These factors led to increased plastic debris in the area in question. Longe'ch as well bears the same problem of high plastic pollution. Most of the fishers and traders prefer settling here due to high fishing activity, thus, the use of plastic containers and plastic-wrapped products is eminent. Namkuse was found to be the least affected amongst the sites sampled, which is attributable to the sparse population density in the area.

Plastic density along Ferguson's Gulf

The findings of the present study indicated that Daraja and Namakat had an average density of 2 plastics m^{-2}; while at Kenya Oil and Longe'ch the average density was 1 plastic m^{-2} (Fig. 7). Namkuse on the other had indicated that one could easily miss getting a plastic in 1 m^2 area of the site. The intensity of 2 plastics per m^{-2} in Daraja and Namakat indicates higher pollution potential in the two sites compared to the others.

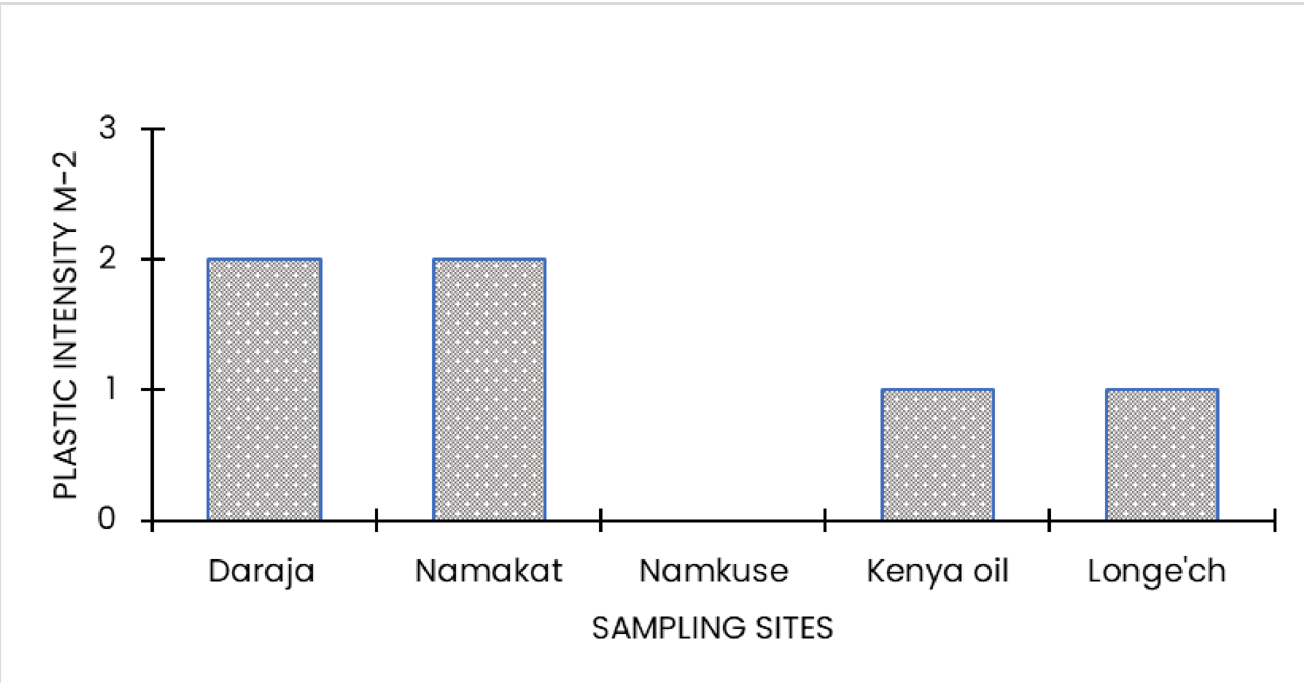

Figure 7. Density of plastic debris in various sampling sites along Ferguson's Gulf Lake Turkana.

Conclusion and recommendations

Ferguson's Gulf exhibited high level of plastic pollution that requires proper management. Daraja had the highest level of plastic pollution, followed by Namakat, Kenya Oil and Longe'ch, respectively.

Polyethylene terephthalate (PETE) e.g., beverage, water and cooking oil bottles consituted the bulk of the plastic pollutants in the Ferguson's Gulf. Low density polyethylene (LDPE) such as shopping bags and squeeze bottles were the second highest plastic pollutants, with Longe'ch and Kenya Oil sites taking the lead in this plastic type. Lack of proper management of the plastic waste along Ferguson's Gulf pose a significant threat to aquatic life in the study area.

There is need to establish solid waste collection points in the area to contain the spread of plastics to the Lake and adjacent environment. Beach Management Units, in collaboration with the County Government should come up with ways of managing plastic wastes in the respective beaches to reduce this plastic menace at the respective sites The enforcement of NEMA regulations banning the use of single-use plastic bags is to ensure the long-term reduction of plastic pollution. Capacity building and sensitization of all stakeholders should be undertaken on a consistent basis to encourage responsible use and disposal of plastics.

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The efficacy of fisheries co-management amidst the impacts of climate change: A case of Lake Baringo Beach Management Units (BMUs), Kenya

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Abstract

There is a common agreement that establishment of co-management through the Beach Management Units (BMUs) is beneficial to the fisher community and other stakeholders as regards promoting their participation in sustainable fisheries resource exploitation. This study evaluated the efficacy of co-management amidst climate change impacts on the Lake Baringo fishery. Information and data were collected through site observations, and questionnaire-led interviews involving the key informants and BMU members. Hydrological and fisheries production (total biomass and fish composition) data were accordingly, obtained from the Water Resources Authority (WARA) and Kenya Fisheries Service (KeFS). The impact of climate change, mirrored by fluctuations in Lake water level was positively correlated to the fishery productivity based on reported fish landings. With regard to fisheries co-management, the study reported corruption among BMUs (61%), lack of awareness on BMU regulations (16.8%), limited enforcement (MCS) (16.7%) and inadequate BMU member welfare (1.1%) as the mains factor underpinning BMUs managing deficit resulting to co-managements inefficacy. However, despite the described inadequacy, there is need to sustain the achievements so far attained in promoting co-management and ecosystem sustainability, as enforcement of laws and regulations can be a challenging undertaking without government support. Therefore, the national and county governments should ensure the provision of financial and material support to enhance the BMUs' capacity to effectively undertake co-management functions.

Keywords: Lake Baringo, co-management, BMU, climate change, fisheries

Introduction

The Kenyan fisheries sector plays a significant role in employment and income generation. During the year 2021 the sector supported a total of 65,000 people directly as fishermen and 70,000 fish farmers with 149,000 stocked fish ponds (FAO, 2022). In 2021, the total fish production was 163,702 metric tonnes worth 30.38 billion Kenya shillings (KNBS, 2022). This represented an 8.2% increase in production compared to 151,289 tonnes worth 26.25 billion Kenya shillings landed in 2020 (KNBS, 2022). The increase in the value was mainly due to catches from industrial vessels and the increase in prices based on the demand and supply impacts on the fish prices. As has been the trend with Kenyan fishery in the past, most of the production was from inland capture fisheries, amounting to 115,353 metric tonnes, with an ex-vessel value of Ksh. 17.4 billion. The principal inland fishery contributor was Lake Victoria, followed by lakes Turkana, Naivasha and

Baringo (KeFS, 2022).

Despite fisheries production reported from Kenyan inland waters, numerous challenges including climate change, pollution and common property utilisation ascribed to unlimited access management are deemed as to contributors to the loss of the lake's biological wealth (Ochieng *et al.,* 2013). Lake Baringo fishermen have been reported to have a varying degree of involvement in the fisheries sector, where some fish only as part-time or on a seasonal basis, while others are full-time fishermen (Walumona *et al.,* 2024). Issues observed to be of immediate concerns to Lake Baringo fisheries are: non-compliance to fisheries regulations, use of illegal fishing gears and methods, increasing fishing efforts due to open access, declining stocks and biodiversity, conservation of the resource and environmental and socio-economic issues such as cross border fishing and fish trade (Nyakeya *et al.,* 2020).

Originally, fisheries management in Kenya (including Lake Baringo) was centralized under the national government (Imende *et al.,* 2005). However, due to an increase fishing effort and rise in illegal practices to meet the demand for fish as well as increasing population in the lake's basin, the central management approach was reported to be unsustainable and uncontrollable (Odoli *et al.,* 2022). Involvement of all stakeholders was deemed necessary as had earlier been witnessed around other Kenyan lakes (i.e., establishment of BMUs along Lake Victoria from 1998 to 2000) and the Kenyan coast, occasioning the establishment of Beach Management Units (BMUs) as a co-management approach to fisheries management (Imende *et al.,* 2005; Obiero *et al.,* 2015).

The main objective of co-management was to give all stakeholders a platform for a collaborative and cooperative partnership for the sustainable fisheries management and improved livelihoods of fishing communities (Ojwang *et al.,* 2009). According to harmonized standards structure and operating manual for the BMU's, the BMU is composed of a BMU assembly, a BMU executive committee and various sub-committees. The BMU is headed by an executive committee that is composed of a Chairman, Assistant /Chairman or Vice Chairman, Secretary, Assistant Secretary, Treasurer and committee members.

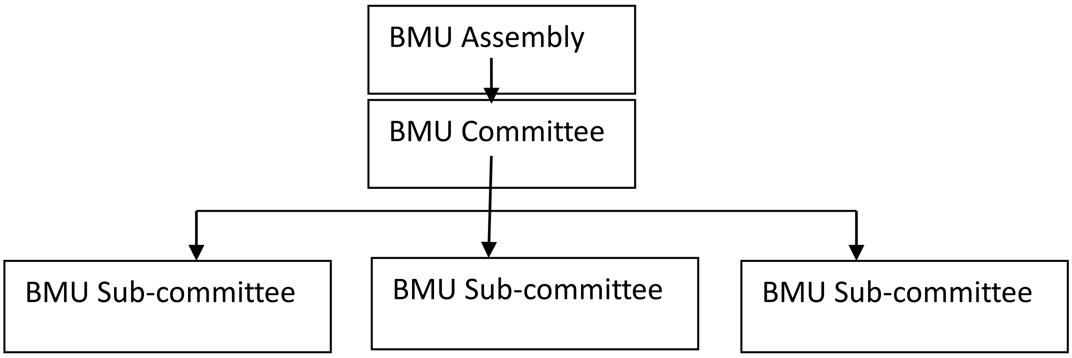

Figure 1. Schematic diagram representing BMU structure.

Since the BMUs establishment, it has had successes with regards to awareness creation, training, cross border lessons and networking (Obiero *et al.,* 2015). However, serious challenges underlay implementation of the co-management mandate where communities do not prioritize the bottom up (down-top) control measures in the fisheries sector as opposed to meeting their immediate needs (Kolding *et al.,* 2014). As opposed to the BMUs being an instrument for implementing fisheries policies, it has been observed that the fishers consider it an instrument for conflict resolution and solving local problems (Odoli *et al.,* 2022). Lately, the BMU's role has now been reduced to price regulation, securing access to shared fishing grounds, markets and financial assistance, and pretty much not at all involved in dealing with illegal fishing activities ascribed to corruption (Kolding *et al.,* 2014). To date, compliance to regulations on fishing gears and legal fish sizes has not been resolved by co-management in Lake Baringo (Pers. Comm. CFO, 2024). Co-management runs a greater risk of failure if the bottom-up regulations and enforcement cannot be understood and supported by the fishers (Odoli *et al.,* 2022).

There is lack of information on the capacity, commitment and willingness of the fisher folk to participate effectively in fisheries management and development activities. Several studies assessed the extent of community involvement in fish management, and perceptions towards fisheries regulations and constrains (Obiero *et al.,* 2015; Odoli *et al.,* 2022). Considering the impacts of climate change and declining Lake Baringo fishery, this study was designed to assess the efficacy of co-management in Lake Baringo amidst climate change impacts.

Materials and methods

Study Area

The study was conducted along Lake Baringo, a shallow freshwater lake in the Eastern Rift Valley of Kenya. Its fishery has been reported to be poor, comprising of three commercially important species (*Oreochromis niloticus baringoensis*, *Clarias gariepinus* and *Protopterus aetiopicus*) while *Barbus* spp. *and Labeo* spp. rarely appear in the catches. The decreased fish diversity is thought to be due to overfishing and limnological changes (Hickley *et al.,* 2004)

The lake surface has previous been reported to cover slightly over 130 km^2, with wide fluctuations as a consequence of Lake water level fluctuations due to climatic influences (Kallqvist, 1987; Hickley *et al.,* 2004; Omondi *et al.,* 2013). However, it has recently been reported to be approximately 250 km^2 during the highest water level reported in early 2020 (Nyakeya *et al.,* 2020). The catchment area is about 6820 km^2 and includes a large part of the Western escarpment of the Kenyan Rift Valley where most of the water is sourced (Ondiba *et al.,* 2018). This study focused mainly on three main fish landing sites namely Kambi Ya Samaki, Kokwa and Loruk in 2022 (Fig. 2) and data obtained from the Water Resources Authority (WARA) and Kenya Fisheries Service (KeFS).

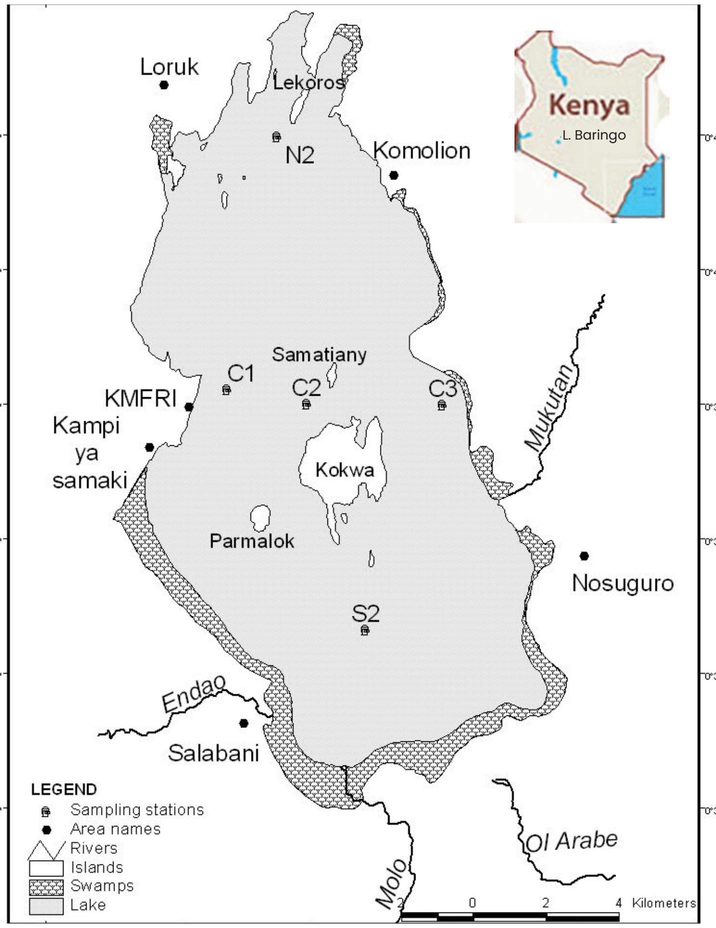

Figure 2. Map of Lake Baringo depicting the three main landing sites/BMUs where the study was undertaken (Source: Authors)**.**

Sampling

The study population comprised of fisheries resource user groups directly involved in capture fisheries, fish trade and fisheries management. A multi-stage sampling approach was adopted where large clusters of the population were divided into smaller clusters in several stages in order to make primary data collection more manageable. Respondents were selected randomly from among the fisheries resource user groups at each landing site.

Primary data collection

Primary data was collected by a team of 5 personnel who were introduced and guided at the chosen landing sites by respective BMU executive officials present. The Beach Management Unit (BMU) officials aided the research team in identifying and assembling together BMU members for the questionnaire led interviews. The questionnaires, which targeted mainly BMU members (active fishers, boat owners, boat crew, traders and processors) were administered in either Kiswahili or English, since these were the most favorable dialects of interaction. Key informant interviews were administered only to BMU officials. Relevant secondary information utilized included information from key informants and published journal papers or technical reports to triangulate results.

Direct observation mainly entailed examination of the lake and surrounding environment, fishing and trading infrastructure and activities, familiarization with dominant fish species landed at the study sites, and filming of spectacular and relevant scenery and activities at the landing sites. At the end of each study site visit, a recap session was held to deliberate on progress made, difficulties encountered and team member experiences during the interview process.

Hydrological and fisheries data collection

Hydrological data were obtained from the Water Resources Authority (WARA) in Rift Valley Basin in the form of daily lake level recordings that were averaged on a monthly and annual basis for the period from 1956 - 2018.

Collection of fisheries data (total biomass and fish composition) was done every month and focused on three landing sites which are considered major in the area covering the Northern, Central and Southern sides of the lake to allow the coverage of the whole lake. Lake Baringo fisheries data used in this study included fisheries yield and value data from 1995 to April 2021 and growth data, in particular condition factors (total length and weight) for 1995 - April 2021. Data on species composition of yield (2008 – 2020) The relative condition factor (Kn) was estimated for each species for the same period following Cren's equation (Cren, 1951) modified and adopted by Ondhoro *et al*. (2016).

Data Analysis

The raw information and data collected was pooled, entered, cleaned and stored electronically using statistical packages (Microsoft Excel and SPSS Version 20), before descriptive data analysis, graphical representation and interpretation.

Results

Study sample statistics

The percentage composition of the respondents was 58% men and 42% women. The age ranged from 18 to 71 years, with 63% being below 50 years while 47% were above 50. 67% of the respondents were owned at least one boat. The fishermen used gillnets (GN) and longline (LN) for fishing. The longline was the most commonly used gear with 39%, trailed by gillnets at 22%, while 39% were using both gillnets and longlines (Fig. 3).

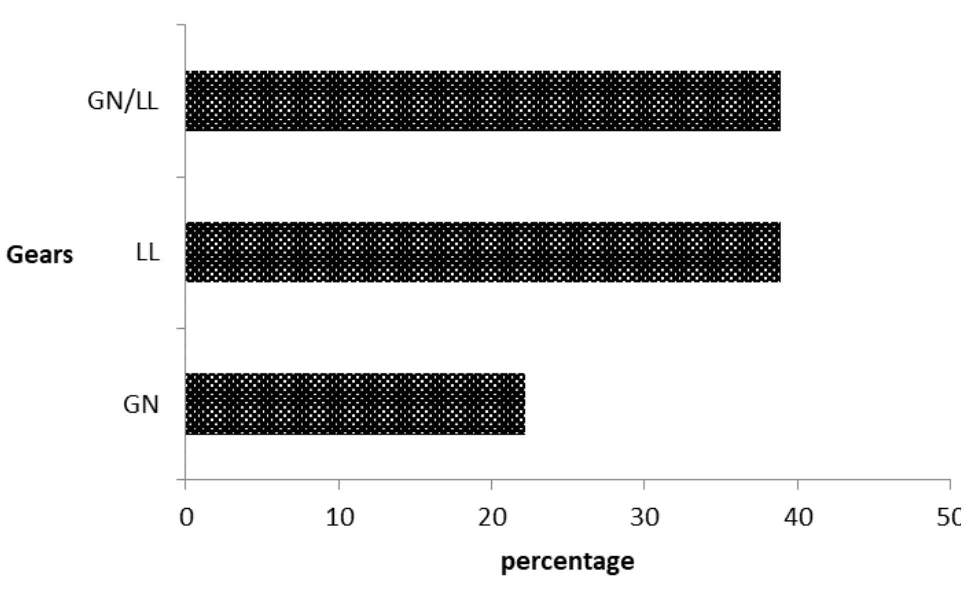

Figure 3. Percentage of gear types used by fishermen.

Majority of the fishers, 53% were educated to primary level whereas, 26% had secondary level education and 11% had attained tertiary education. Eleven percent (11%) had not gone to school (Fig. 4).

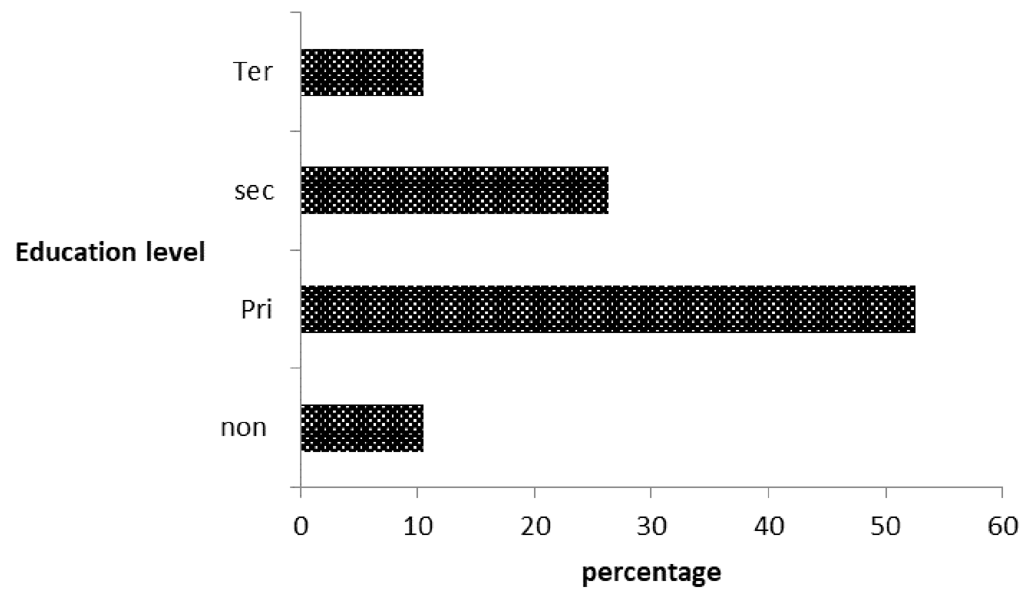

Figure 4. Education level of the fishers in Lake Baringo, Kenya.

The key respondents' information is shown in table 1.

Table 1. Key informants' data collected from the BMUs at three landing sites/beaches

Management Committee issues	Kambi Ya Samaki	Kokwa Island	Loruk
Key departments	Health, education, social, patrol & welfare	Health, education, boats, gears & boats gears & nets, welfare,	Sanitary, education, security, patrol, welfare, planning, finance, development, infrastructure
		Marketing & price, MCS & banda,	Infrastructure
Last management meeting	Apr-2020	May-2020	Feb- 2020
Frequency of BMUs meeting	Weekly meetings	Weekly meetings	Quarterly
Key discussions	Health, welfare, patrols,	Boats & nets; reshuffling & patrols	Development, education
Actions difficult to implement	Control bad fishing practices	None	Members migration
Frequency of general assembly	After 3 months	Twice a week	Anytime depending as need arises
Do you have a patrol boat/engine	Yes	Yes but no engine	Yes
Frequency of patrols	Anytime as need arise	Weekly	Rarely but in collaboration
Last patrol date	1 Week back from today	1 Week back from today	2 months from today
Any collaborators during patrols	Fisheries	None	None
Aware of breeding or fishing grounds	Yes	Don't know	Yes
Awareness on climate change issues	No	No	No

Key issues affecting BMUs operations

Key issues affecting the BMUs at surveyed landing site were assessed and tabulated as depicted in Table 2 below. Majority of the respondents perceived fish price fluctuations as the key issue or challenged faced by respondents at most landing sites. The other key issues reported were the declining fish landings, insecurity, post-harvest losses and illegal fishing methods. Issues of lesser concerns to respondents included pollution, conflict over fishing grounds and lack of funds for monitoring control and surveillance (MCS).

Table 2. Key issues affecting the landing sites.

Key issues	Percentage and frequency of respondents			
	Overall %	Frequency in BMU sites		
		K-Samaki	Kokwa	Loruk
Fish price fluctuations	34.5%	7	20	3
Decline in fish landings	16.1%	2	7	5
Insecurity	14.9%	4	6	9
Post-harvest losses	12.5%	8	1	2
Illegal fishing methods	8%	1	3	3
Pollution	4.5%	2	1	1
Conflict over fishing grounds	4.6%	1	0	3
Lack of funds to purchase fuel for MCS	3.4%	1	0	2
Poor road network	1.1%	0	1	0

* MCS= Monitoring control and surveillance.

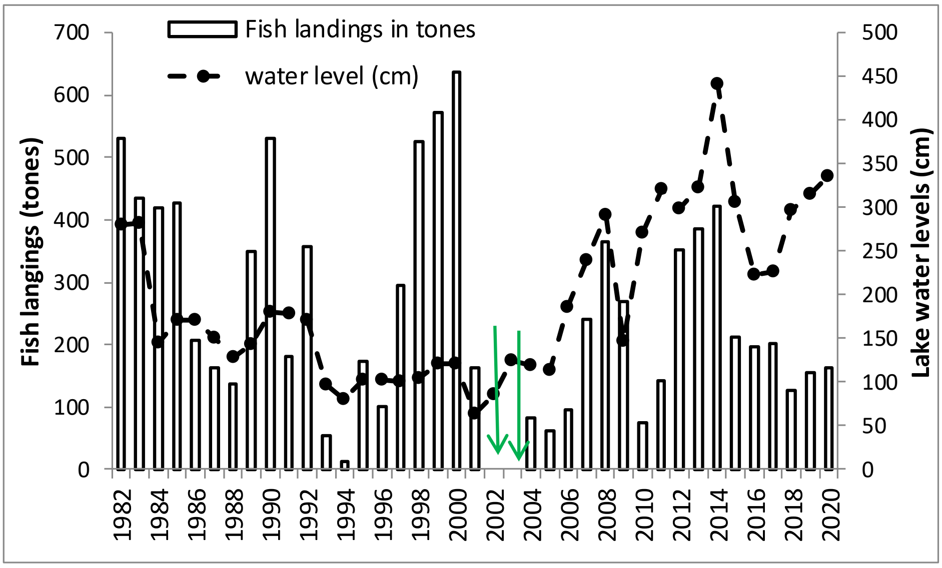

Figure 5. Lake Baringo fishery yield in metric tonnes and Lake water levels (WL).

Fisheries productivity and hydrological indices relationship

Annual fisheries yield in Lake Baringo from 1982-2020 has fluctuated greatly from approximately 8 metric tonnes in 1994 to 465 metric tons in 2000, averaging close to 187 metric tonnes (Fig. 5). These results indicate that the water level change is the main driver of fluctuations in fish species biomass in the lake. Average monthly fishery yield from 1995-2020 showed seasonality in fishery yield, an indication that the lake is more productive from April to August where its fishery peaks and later reduces from early September to March

Only two species out of the four species show a positive correlation between condition factor and lake levels (*B. intermedius*) and between the condition factor and the max annual lake water level amplitude (*O. niloticus*). This result shows a kind of biological dependency of *B. intermedius* and *O. niloticus* on the water level in the lake, while *C. gariepinus* and P. *aethiopicus* do not show a clear biological dependency on the hydrological regime. (Table 3)

Table 3. Pearson correlation coefficient between mean annual condition factor and the five hydrological indices of the four most important fish species caught at Lakeside station.

V1	v2	r	n	prob	SS
O. niloticus					
condiction factor (Kn)	MA lake level	-0.045	13	0.884	NS
condiction factor (Kn)	Delta level	-0.260	13	0.390	NS
condiction factor (Kn)	Max annual amplitude	0.691	13	0.009	**
condiction factor (Kn)	ΔLev(y)+ ΔLev(y-1)	-0.121	13	0.693	NS
condiction factor (Kn)	WLs (WLamp + Wldelta)	0.143	13	0.640	NS
P. aethiopicus					
condiction factor (Kn)	MA lake level	-0.478	13	0.099	NS
condiction factor (Kn)	Delta level	0.098	13	0.750	NS
condiction factor (Kn)	Max annual amplitude	0.084	13	0.785	NS
condiction factor (Kn)	ΔLev(y)+ ΔLev(y-1)	-0.073	13	0.813	NS
condiction factor (Kn)	WLs (WLamp + Wldelta)	-0.043	13	0.890	NS
C. gariepinus					
condiction factor (Kn)	MA lake level	-0.454	13	0.119	NS
condiction factor (Kn)	Delta level	0.158	13	0.607	NS
condiction factor (Kn)	Max annual amplitude	-0.148	13	0.630	NS
condiction factor (Kn)	ΔLev(y)+ ΔLev(y-1)	0.275	13	0.364	NS
condiction factor (Kn)	WLs (WLamp + Wldelta)	0.226	13	0.458	NS
B. intermedius					
condiction factor (Kn)	MA lake level	0.811	13	0.0008	***
condiction factor (Kn)	Delta level	0.154	13	0.615	NS
condiction factor (Kn)	Max annual amplitude	0.228	13	0.453	NS
condiction factor (Kn)	ΔLev(y)+ ΔLev(y-1)	-0.349	13	0.242	NS
condiction factor (Kn)	WLs (WLamp + Wldelta)	-0.272	13	0.369	NS

SS: Statistical significance, 'y' in subscript parentheses gives, if any, the time lag between variables. NS, not significant, *** is significant at 0.1% level, and ** is significant at 1% level.

Assessment of BMUs performance in co-management of lake fisheries

Record keeping

In this study BMUs were found to maintain registers of members, boats and catches landed (Table 4), but with poor records of gears and revenue collected, although a significant group of respondents (12.6%) weren't sure. Most of the respondents (40.2%) reported awareness of the inventory of existing infrastructures within the BMU. During the assessment, the beach registers were cross checked to confirm existence and frequency of records updating.

Table 4. Types of register and records maintained by BMUs.

Types of register and records	Percentage and frequency of respondents			
	Overall %	Frequency in BMU sites		
		K-Samaki	Kokwa	Loruk
Member's register	40.2%	12	12	11
Boat register	21.8%	6	11	2
Catch records	14.9%	4	2	7
Don't Know	12.6%	1	10	0
Gear's register	3.4%	1	0	2
BMU members, boat and gears	3.4%	0	3	0
Visitors book	2.3%	2	0	0
Revenue records	1.1%	1	1	0

BMU efficacy

According to the respondents (Table 5), welfare needs, conflict resolution, enforcement and awareness creation ranked as the best performed roles by the BMUs, although they perceived corruption within the BMUs as an issue of concern. Generally, the respondents still considered the BMUs as the best channels (33.8%) through which arising conflicts are resolved, besides the use of the area chiefs (4.9%) and courts (2.5%) (Data not provided). This could be due to the acceptance by the respondents of the existence of several BMU by-laws complementing the prescribed BMU guidelines.

Table 5. Roles adequately / inadequately addressed by BMUs.

	Roles adequately addresses by BMU					Roles inadequately addresses by BMU			
	Percentage and frequency (freq) of respondents					Percentage and frequency of respondents			
	Overall %	Freq. in BMU sites				Overall %	Freq. in BMU sites		
		K-Samaki	Kokwa	Loruk			K-Samaki	Kokwa	Loruk
Enforcement	17.6%	3	7	2	Limited enforcement	16.7%	3	0	0
Welfare	35.5%	5	12	7	Inadequate welfare	5.6%	1	0	0
Awareness creation	13.2%	2	6	1	Awareness creation	16.8%	1	2	0
Conflict resolution	33.8%	7	9	7	BMU are corrupt	61.1%	3	5	3

Discussion

The percent composition of the respondents was majorly men who are mainly fishermen (upstream value chain) with women (minority) gainfully engaged in the downstream value chain activitie,s specifically processing and marketing nodes. Studies have revealed women, and particularly in developing nations to be participating in the downstream fisheries sector (constitute 47% of fisheries workers) (Wamukota, 2009; Mills *et al.,* 2011). A majority of Lake Baringo fishery value chain actors were less educated to primary school level, with a marginal constituent having attained tertiary education. This could be because fishing and fisheries business in the artisanal setup, as is the case of Lake Baringo, isn't considered lucrative and thus unattractive to the educated class (Oloko *et al.,* 2022).

The roles of BMU's have continued to evolve from being localized and welfare-based to networked and harmonized roles so as to meet the changing environmental, political and socio-economic needs in the fishery sector (Odoli *et al.,* 2022). The roles are more focused on the sustainable management of the fishery resource. This study points to some of the underlying challenges towards the progressive growth of the BMUs, especially with regard to execution of their mandates. Fish price was identified as the most challenging aspect for the BMUs to control (34.5%), while poor road network and interference from revenue collection officers, though present, were amongst others, the least of BMUs' concern. The growing demand for fish has led to an increase in prices (Odoli *et al.,* 2019), where under such conditions, every fisherman strives to maximize his or her benefit oblivious to the damages caused to the future fisheries stock. This notwithstanding, fishermen along Lake Baringo sell fish to agents who are also the boat owners, depriving them of the bargaining power and thus they sell fish at low prices.

Overfishing reported in Lake Baringo is ascribed to the propensity to use illegal gears (below recommended or legal mesh sizes of 5"), indiscriminate gears, outlawed fishing techniques and mass–target fishing methods (Nyakeya *et al.,* 2020; Walumona *et al.,* 2023).

The results on the relationship between fishery productivity and hydrological indices showed good associations between Lake water level and yield, after correlation analysis. These relations depict positive impact of hydrological variables especially rising Lake Baringo water levels on the fisheries productivity. Studies have shown that seasonal fluctuations in water level are related to fluctuations in fish productivity (Junk *et al.,* 1989; Kolding and Zwieten, 2012). The higher the water level in an ecosystem, the higher the fisheries productivity (Kolding *et al.,* 2016). Changes in the littoral habitat of Lake Baringo influences ecological functions that boost fishery production in a semi-arid area where fishing is the principal activity for the riparian communities. Decline in lake level leads to large losses of the open water habitat reducing the carrying capacity of species that dominate its pelagic habitat. According to Anton (2016) and Karp and others (2019), the higher the average change in lakes water levels, the higher the fisheries production or yields. The effects of habitat variations and their distribution on the fisheries of Lake Baringo are also functional of human population densities around the lake. However, the study notes that riparian communities' livelihoods depending on activities along the shores such as community resident areas, pasture etc., were negatively impacted or affected by the lake rising water levels, but this was not within the scope of the current study.

In regard to co-management efficacy, all stakeholders appreciate that regulations are important, but the compliance system with fisheries regulations on the lake is currently low as illustrated by high non-compliance noted by stakeholders and observed at the landing sites. To date, compliance to regulations such as banned use of illegal gears and post-harvest management (loss mitigation) remains a challenge to BMUs and policy makers. This necessitates the need to increase illegal fish gears detection rates by increasing surveillance. Therefore, BMU's need to be developed to the level where they have the capacity to work and conduct their co-management functions.

Conclusion and recommendations

This study has shown that climate change as depicted by the fluctuations in the Lake Baringo water level are interrelated with fluctuations in fish productivity, where a rise in water level leads to an increase in fish catches. During the sustained rainy years, the size of the lake was observed to increase leading to more habitats and refugia suitable for breeding of fish, especially *O. niloticus.* More so, the findings show high variations in expected BMUs performances among the landing sites, but sharing similar challenges. The BMUs perform a very vital role but cannot match to the expectations due to declining fishery resource, ascribed to high fishing pressure which ideally should be the BMUs mandate, and climate change variables, especially fluctuations in Lake water level. Therefore, the main threats to Lake Baringo fishery are overfishing and use of illegal gears, as well as climate change impacts.

There is need to prioritize support towards the urgent needs emerging from the BMUs interviewed, especially with regards to enforcement of fisheries regulations. Therefore, the National government through KeFS and County government should provide financial and material support in expanding the capacity of BMUs to perform and promote sustainable fisheries management.

Acknowlegements

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Socio-economic dynamics and resource management challenges in Lake Victoria: Implications for Kenya's Blue Economy

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Abstract

The Blue Economy, which encompasses sustainable use of aquatic resources for economic growth, improved livelihoods, and environmental health, has gained global recognition as a critical driver of sustainable development. Socio-economic studies play a fundamental role in enhancing the Blue Economy by providing insights into human interactions with marine and freshwater ecosystems, economic dependencies, and social dynamics that influence sustainable resource utilization. This paper highlights the critical role of socio-economic studies in shaping a sustainable and inclusive Blue Economy. This is because, these studies help in assessing the economic value of marine industries such as fisheries, tourism, and maritime transport, while identifying socio-economic challenges such as poverty, resource conflicts, and policy gaps. Additionally, socio-economic research informs evidence-based policymaking, promotes equitable benefit-sharing, and fosters community engagement in Blue Economy initiatives. Through integrating socio-economic analyses into Blue Economy strategies, governments and stakeholders can achieve sustainable resource management, job creation, and climate resilience, ultimately ensuring long-term economic and environmental benefits. The current paper showed that fishing dominated Lake Victoria uses and therefore the fishing activities led in encountering disputes with other users. The most dominant illegal activities were those mostly mentioned in previous literature and they were mainly resource use conflicts, illegal, unregulated and unreported (IUU) fishing and pollution, among others. The paper recommends the creation of a regulatory system or a policy framework for the Lake's uses that is crucial to lake management through the use of citizen science mechanisms.

Keywords: dynamics, Blue Economy, socio-economics, citizen science, studies

Introduction

As nations look to maximize the economic potential of seas, oceans, and other bodies of water while maintaining environmental sustainability, the idea of the "Blue Economy" has drawn a lot of attention recently. A variety of industries that support economic growth, job creation, and food security are included in the Blue Economy, such as biotechnology, fisheries, maritime transportation, coastal tourism, and renewable energy (Choudhary, 2021). A thorough grasp of the socio-economic elements influencing the management of freshwater and marine resources is necessary to achieve a sustainable and inclusive Blue Economy. Examining the social structures, economic relationships, and policy frameworks that influence how people interact with aquatic habitats, socio-economic studies are essential in this respect (Stojanovic *et al.*, 2016). Evaluating the economic worth of marine resources and industries is one of the main ways socio-economic studies contribute to the Blue Economy. Policymakers and stakeholders can make better judgments about resource allocation and investment priorities if they have a thorough understanding of the economic importance of fisheries, aquaculture, and marine-based tourism (Payet, 2006). Socio-economic research helps to ensure that economic policies are in line with the sustainable development goals (SDGs) by shedding light on how the Blue Economy contributes to employment, livelihoods, and the Gross Domestic Product (GDP) at the national and regional levels.

The social aspects of the Blue Economy, including the roles and vulnerabilities of various stakeholder groups, are highlighted by socio-economic studies. Indigenous populations, coastal communities, and small-scale fishermen frequently rely significantly on marine resources for their livelihoods (Andrews, *et al.*, 2021). In order to ensure fair benefit-sharing and lessen socio-economic inequities, research on gender dynamics, access to marine resources, and social inequality helps advance inclusivity in Blue Economy projects. Policymakers can create initiatives that strengthen social resilience, empower marginalized communities, and boost general well-being by taking socio-economic factors into account (Jewett, *et al.*, 2021). Addressing environmental sustainability issues in the Blue Economy also heavily relies on socio-economic research. The long-term sustainability of ocean-based enterprises is threatened by overfishing, marine pollution, habitat loss, and climate change (Mekouar, 2023). By identifying the social and economic factors that contribute to these environmental problems, socio-economic assessments facilitate the creation of policies that support sustainable resource management. Strategies for encouraging sustainable seafood consumption and responsible use of marine resources, for instance, can be informed by research on consumer behavior, market incentives, and regulatory frameworks (Penca, 2020).

In the Blue Economy, socio-economic research backs evidence-based government and policymaking. Researchers assist governments in creating policies that strike a balance between environmental preservation and economic growth by offering data-driven insights into labor markets, economic trends, and the efficacy of policies. Informed by socio-economic research, effective governance processes support the creation of marine protected areas, international cooperation, and dispute resolution—all of which are essential for maintaining ecosystem services and biodiversity (DI Cintio *et al.*, 2023). Through offering a comprehensive understanding of the economic, social, and environmental linkages within freshwater and marine systems, socio-economic studies are essential for advancing the Blue Economy. Governments and stakeholders can support sustainable resource management, improve social fairness, and build economic resilience by incorporating socio-economic research into Blue Economy policies. Investing in socio-economic research will be crucial to securing the Blue Economy's long-term success and protecting marine ecosystems for coming generations, as the world increasingly turns to the seas as a source of sustainable growth. Given the role played by socio-economic research in policymaking, equitable benefit-sharing, and fostering community engagement in Blue Economy initiatives, the current paper highlights the critical role of socio-economic studies in shaping a sustainable and inclusive Blue Economy of Lake Victoria, Kenya in order to give room for specific mitigation measures and to foster value additions in areas that appear to have certain gaps.

Materials and methods

Study Area

The study was conducted in the five riparian counties: Kisumu, Siaya, Busia, Homabay, and Migori within Lake Victoria, Kenya whereby a total of 26 landing sites were sampled. Kisumu (2), Siaya (3), Busia (3), Homabay (12) Migori (5), and other lake users such as Luanda Kotieno ferry terminals, Mbita ice plant, Kenya Electricity Generating Company (KENGEN) station, Kisumu Water and Sewerage Company (KIWASCO), Siaya-Bondo Water and Sewerage Company (SIBOWASCO), Homabay Water and Sewerage Company (HOMAWASCO), Kenya Rural Roads Authority (KERRA), Kenya Urban Roads Authority (KURA) and Kenya National Highway Authority (KENHA).

Site selection

After stratification at several levels (administrative, landing site nature, and lake uses), the study sample was determined. The beach's level of activity and the availability of the necessary target groups of lake users were taken into consideration while selecting the landing spots. Scheduling restrictions and the limitations of available resources significantly limited the actual sample size. Both urban and rural landing options were considered in each county.

Data collection and analyses

Fisher communities, local administration, ward representatives, government officials in KURA, KERRA, and KENHA, as well as water abstraction and transport companies, hydroelectricity companies, and waste water discharge, were interviewed one-on-one to administer a structured online questionnaire anchored in Kobo to 317 respondents. Prior appointments for the interviews and the study's participative methodology, which entailed following up with respondents at their designated work stations, were credited with the high response rate. Depending on the predominant dialect in certain landing sites, the enumerators translated the interview questions into either Luo or Kiswahili, even though the data collection tool was recorded in English.

The acquired electronic data was downloaded into MS Excel before being processed and exported to Statistical Package for Social Sciences (SPSS) for further analyses. The SPSS Version 28.0.1.1 was employed for statistical analysis, focusing on relationships between key variables such as socio-demographics, uses, regulatory frameworks, conflicts and challenges. Descriptive statistics including means, frequencies, and percentages, were calculated to summarize the data.

Results and discussion

Socio-demographic characteristics

Table 1 provides a summary of the respondents' attributes. For the study, a sample of 319 lake users was selected. The majority of respondents (n = 114; 36.5%) were in the 36–45 age range, and there were comparatively more men (n = 241; 76%) than women (n = 76; 24%). The bulk of users only had O-level education (n = 153; 48.4%) and A'Levels (n = 109; 34.5%), and about 85.2% (n = 271) were married.

Table 1. Socio-demographic characteristics of various users of Lake Victoria, Kenya.

Variable	Categories	n	Proportion
Gender	Male	317	76.0%
	Female		24.0%
Age	18-25	310	10.0%
	26-35		26.8%
	36-45		36.5%
	46-55		17.4%
	>56		9.4%
Marital status	Married	317	85.2%
	Separated/Divorced		0.6%
	Single		10.1%
	Widow/er		4.1%
Education Level	None	316	1.6%
	O Level		48.4%
	A Level		34.5%
	Tertiary		15.5%

Uses of Lake Victoria

In Lake Victoria, a variety of activities occur (Fig. 1). The lake is mostly utilized for fishing and household tasks. According to the majority of respondents (n = 294; 93%), the lake is crucial to their livelihoods and should be managed appropriately (n = 302; 95.3%). Nearly 40 million people in riparian nations depend on the Lake Victoria basin for domestic purposes, fishing, and agricultural output (Okungu *et al.,* 2005). Food, energy, drinking and irrigation water, shelter, maritime transportation, leisure, and a place to dispose off industrial, agricultural, and human waste are all provided by the Kenyan basin. Additionally, it serves as a destination for tourism and biodiversity conservation. Large populations live in the basin and depend on it for industrial development, sale and export, subsistence farming and fishing. Inspite of the lake's significance to the surrounding towns, the respondents reported a sharp rise in lake usage which has degraded the water quality and limited their ability to utilize it efficiently. Therefore, it is crucial that the nation and the different stakeholders work together through concerted effort to guarantee the lake's survival for better livelihoods. Some of the lake's observed usage within the riparian counties are depicted in figure 3.

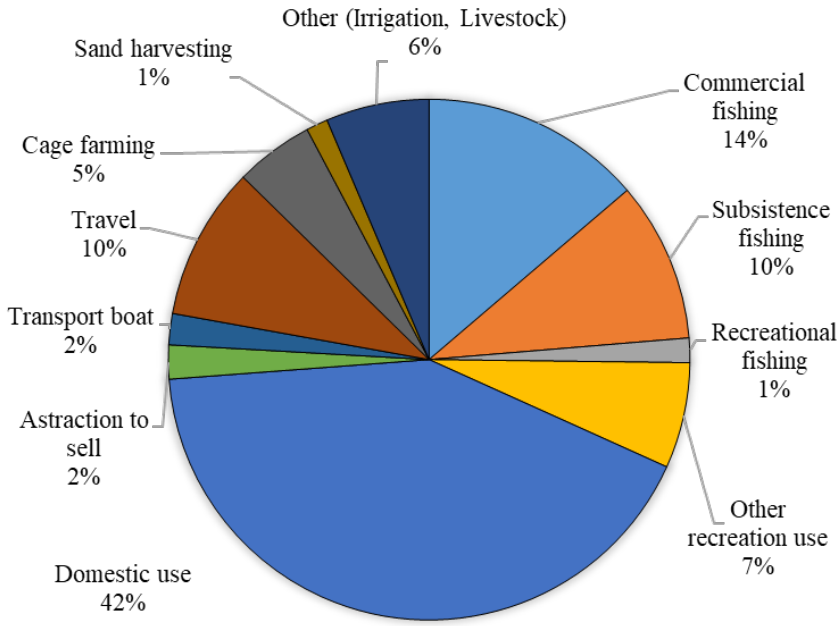

Figure 1. Various uses of Lake Victoria, Kenya.

Perceptions on lake use

Despite the rise in users, respondents reported that there was still adequate room in the lake for their activities (Table 2). However, owing to human-wildlife conflicts and shoreline erosion, safety along the lake was a major concern.

Table 2. Percentage score of uses of Lake Victoria based on the perceptions of the lake-users.

Statement	Percentage	Description
Ability to conduct activities in the lake	82.9	Strongly agree
Unavailability of enough space in the lake to conduct activities	52.1	Neither agree nor disagree
Safety along the shores of the lake	69.0	Agree
Safety in the lake	58.5	Neither agree nor disagree
Conflict with other users when using the lake	68.1	Agree

Challenges of lake uses

Disparities in Lake Victoria's management across ecological, social, economic, and political contexts lead to difficulties in a number of areas. Global environmental change, transboundary problems, human and social aspects, governance structure flaws, and environmental sustainability concerns were all mentioned by respondents (Fig. 2). Deteriorating water quality as a result of rising pollution from human activity is one of the environmental challenges mentioned, which could lead to major health problems. Increased siltation from upstream sources has been noted by cage farmers, interfering with the water depth needed for cage installation. Fish stocks are deteriorating as a result of increasing fishing effort brought on by the lake's free access scheme.

According to several respondents, the co-management regime's poor governance mechanisms made it more difficult for stakeholders to use lake resources sustainably. Because their functions overlapped, the users did not fully comprehend the multi-agency management system. Fishermen stated that other fishermen were destroying and stealing their gear, resulting in financial losses. Attacks by humans on wildlife were also common, resulting in financial and societal damages. Fishermen who fish near the cages have also been accused by cage farmers of stealing fish.

The claimed transboundary problems included Ugandan border patrol agents harassing them and arresting them, which prevented them from using the lake. Additionally, they reported that because they were not following fishery regulations, the local authorities were harassing them. Reduced water levels, severe winds, and temperature variations brought on by global climate change have been shown to contribute to fish mortality and escapees as well as water abstraction for residential and commercial applications. Additionally, floating islands obstructed fish landing sites and cage water abstraction points.

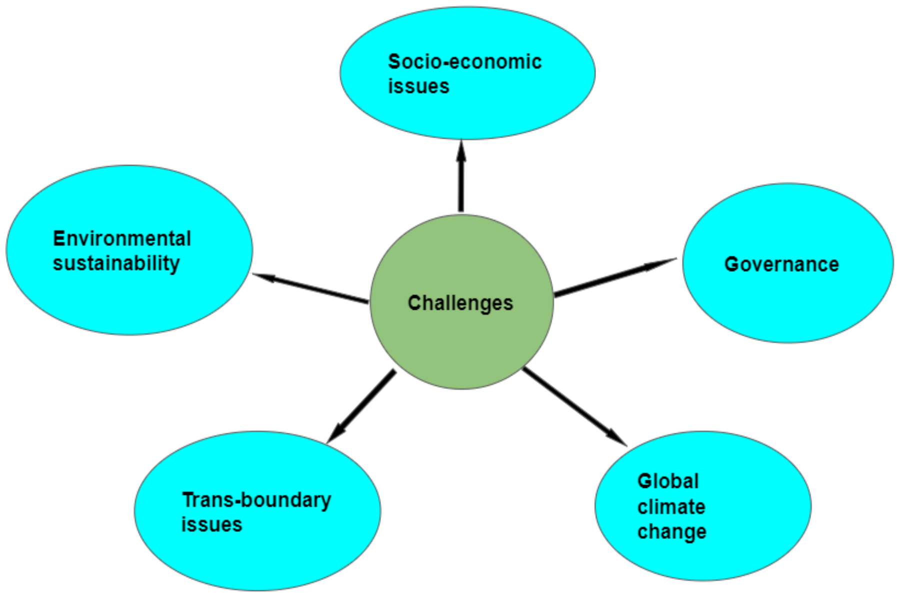

Figure 2. Challenges linked to the use of Lake Victoria, Kenya.

Conflicts between lake users

Figure 3 shows mapping of some of the reported conflicts. About 65.2% (n = 208) of respondents reported having had disagreements with other lake users. Because fisherman are the predominant users of the lake, disputes between them and other users were the most common. Due to the lake's several uses and the lack of information provided by stakeholders regarding its different users, disputes also developed between other users. The Beach Management Units (53.6%), observation (25.4%), National Government officials (13.5%), County Government officials (5.6%), chiefs and elders (0.9%), friends, family, and neighbors (0.6%), fliers, and radio (0.3%) were the primary sources of information. In terms of knowledge about new users of the lake, majority (n = 227; 71.2%) cited Beach Management Unit (BMU) to be the main source of information, followed by observation (n = 73; 22.9), with the least being national government officials (0.5%). This was probably due to the fact that majority of the users of the lake reside within the fishing villages where the BMU is the main policy implementor.

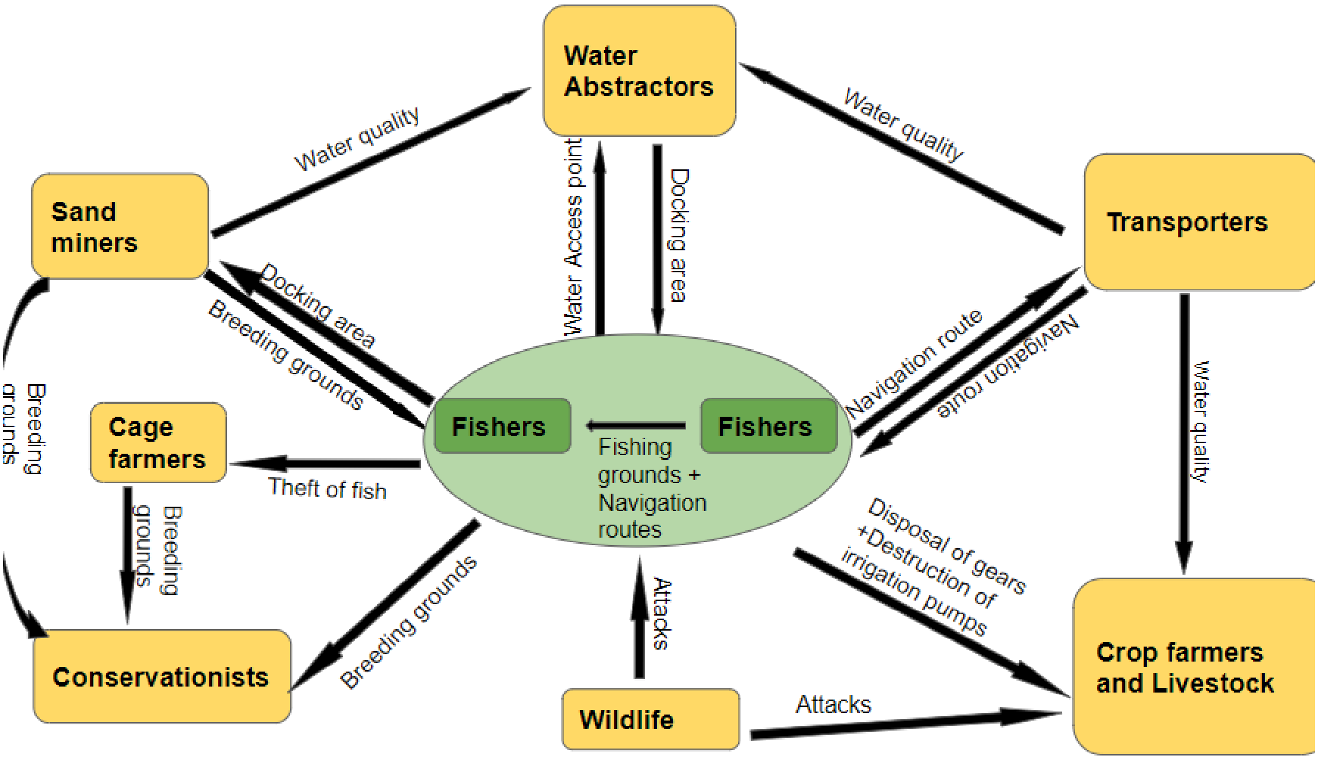

Figure 3. Prominent conflicts amongst the various users of Lake Victoria, Kenya.

Unsustainable activities in the lake

Approximately 85% (n = 272) of respondents said they had seen activities occurring in their lake usage region that they believed shouldn't be occurring (Table 3). These included sand harvesting, illegal fishing, garbage disposal, riparian vegetation removal, an uncontrolled number of cages and fishermen, and lake infrastructure development. They were concerned about the potential long-term health effects of cage farming's using metal frames. Additionally, some crop farmers asserted that they owned the riparian areas they occasionally cleared for farming, which was said to have an adverse effect on water quality due to the use of chemical fertilizers. Waste was also reported to be released into the lake through cleaning in the lake, oil spills, haphazard cage placement, and a shortage of restrooms at landing sites. Another factor contributing to the rise in lake pollution was the washing of cars and motorcycles along the shores of the lake.

Table 3. Activities that were perceived as unsustainable in Lake Victoria.

Activity	Description
Illegal fishing	• Use of monofilament nets • Fishing in breeding grounds • Use of poison • Beach seining
Waste disposal	• Open defecation • Dumping of diapers/sanitary materials/plastic bottles • Bathing/ washing in the lake • Industrial sewage release • Oil spills from boats
Clearing of riparian vegetation	Crop farming along the shores using fertilizers
Sand harvesting	Near breeding grounds
Cage fish farming	• Use of metallic cage frames • Unconsumed feeds • Unregulated number of cages
Fishing	• Unregulated number of fishers • Use of unseaworthy boats
Infrastructure	Construction of hotels near the shore

Regulatory framework

Respondents pointed to a lack of policies and lax implementation of available frameworks, which are necessary for effective governance to gurantee a sustainable Blue Economy. The majority of them (n = 288; 90.3%) recommended the creation of a legal/regulatory system or a policy framework for the lake's uses and proposed the development of a spatial plan is guide lake management and resource utilization (n = 286; 89.7%). Additionally, the respondents expressed willingness to contribute to the plan through community mobilization (n = 140; 43.9%), awareness creation (n = 81; 25.4%), indigenous knowledge (n = 62; 19.4%), and technical skills (n = 36; 11.3%). They also find it important to be involved in the various stages of the plan, such as planning (31.8%), development (20%), implementation (21.9%), and monitoring (26.2%). Obtaining stakeholder feedback was very important to the respondents (n = 287; 90%), with the proposed feedback mechanisms presented in figure 4.

Conclusion and recommendations

Socio-economic studies play a critical role in enhancing the Blue Economy by providing insights into human interactions with marine resources in form of economic dependencies, and social dynamics that influence sustainable resource utilization. The current paper showed that Lake Victoria basin is dominated by an energetic and literate population that can advance Blue growth in the region. Fishing dominates the lake use with majority of the respondents showing an ability to conduct activities in the lake, and with disputes between fishers and other users being the most common. The respondents mentioned the most dominant illegal activities being undertaken in the lake such as IUU, pollution, among others that have similarly been noted in most literature. The paper recommends the creation of a legal/regulatory system or a policy framework for the lake's uses that is crucial to lake management through community mobilization, awareness creation and by applying citizen science mechanisms for lake conservation such as use of indigenous knowledge.

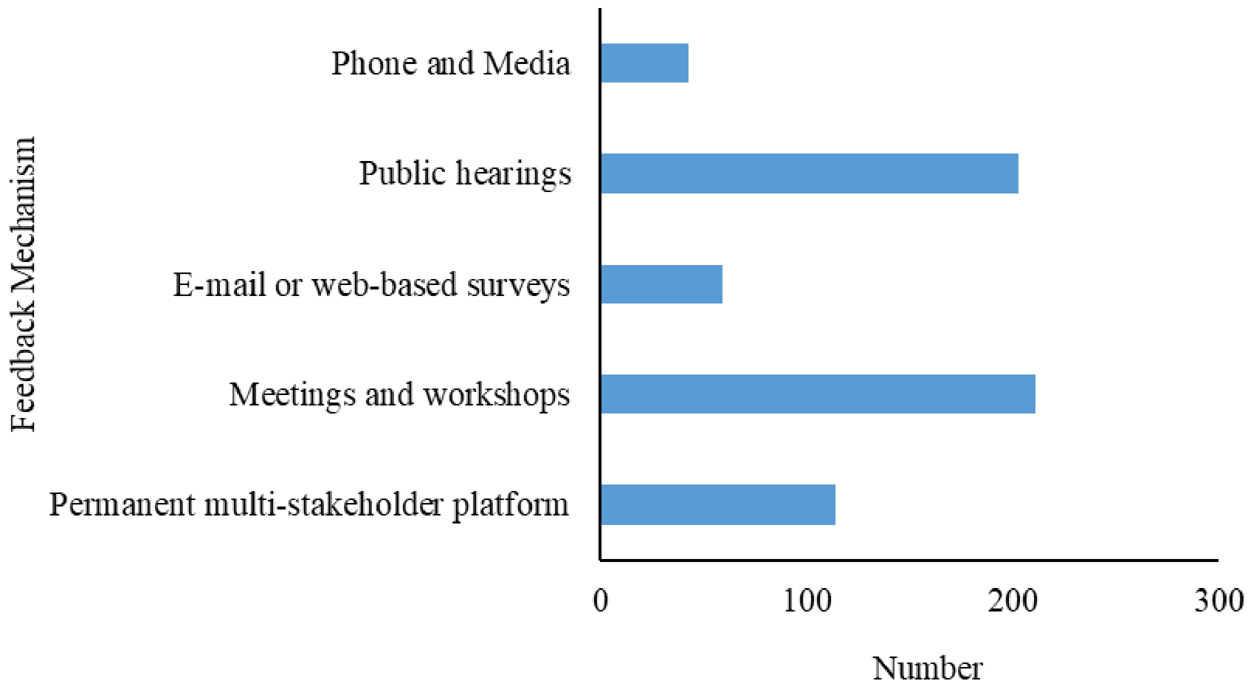

Figure 4. Recommended stakeholder feedback mechanisms.

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Marine organisms: A hidden treasure trove from the Kenyan waters for antimicrobial resistance (AMR)

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Abstract

Reports from the World Health Organization (WHO) indicate a significant increase in the global emergence of drug-resistant human pathogenic microbial strains since 2021. Antimicrobial resistance (AMR) is a significant global public health threat to modern medicine leading to increased mortality. Microorganisms such as bacteria, viruses, fungi, and parasites evolve to resist the effects of antimicrobial medicines. The current pipeline for new antibiotics is insufficient to keep pace with the growing antimicrobial resistance. Novel antimicrobials are essential to combat resistant pathogens and ensure the continued effectiveness of medical treatments. The marine environment, teeming with diverse marine life, including marine sponges, corals, seaweeds, mollusks, sea squirts, fungi and bacteria hold the potential to combat the growing challenge of AMR. These marine microorganisms have been reported to synthesize bioactive compounds including alkaloids, antibiotics, carotenoids, polyketides and terpenoids with potential therapeutic applications. Marine-derived metabolites such as mytilin sourced from *Mytilus galloprovincialis*, jellyfish collagen peptides, Didemnin B from *Trididemnum solidum*, Ergosta-5,7,22-triene-3β,14α-diol (22Z) from *Ganoderma lucidum*, and Bacillomycin D from *Bacillus amyloliquefaciens*, have been reported to exhibit broad-spectrum antimicrobial effects. Kenyan marine waters within the Western Indian Ocean are rich in biodiversity and host a variety of marine organisms with unique biochemical properties. The coastline is characterized diverse marine ecosystems including coral reefs, mangrove forests, seagrass beds, estuaries, lagoons, sandy beaches and rocky shores. A study on a sponge, *Axinella infundibuliformis* from the Kenyan coast revealed its extracts exhibit significant antimicrobial activity against Gram positive bacterial and fungal pathogens. This comprehensive review delves into the untapped treasure troves of Kenyan marine biodiversity, highlighting the promise they hold for novel antimicrobial agents and solutions in the fight against AMR.

Keywords: antimicrobial resistance (AMR), bioactive compounds, chemical structures, marine organisms

Introduction

Globally, according to the World Health Organization's (WHO) latest reports, there were an estimated 450,000 incident cases of rifampicin-resistant (RR) or multidrug-resistant tuberculosis (MDR-TB) and 191,000 resultant deaths in 2021 (Lv *et al.,* 2024). The primary reason for the increase in tuberculosis (TB) incidence is attributed to the impact of the COVID-19 pandemic on TB detection (Falzon *et al.,* 2023). Additionally, the emergence of resistance to artemisinin-based combination therapies (ACTs) for *falciparum* malaria in the Greater Mekong subregion poses a significant threat to global malaria control (Imwong *et al.,* 2017). Efforts to combat this resistance include continuous monitoring of drug efficacy and the development of new treatment strategies to prevent the spread of resistant strains (Ahmed *et al.,* 2024).

The misuse and overuse of antimicrobials in humans, animals, and agriculture are primary drivers of antimicrobial resistance (AMR) (Ahmed *et al.,* 2024). Often referred to as the "Silent Pandemic," AMR demands immediate and effective intervention instead of being viewed as a future threat (Tang *et al.,* 2023). AMR poses a threat to modern medicine, making routine surgeries, cancer treatments, and organ transplants riskier due to the potential for untreatable infections (Salam *et al.,* 2023). Without preventive measures, projections indicate that by 2050, AMR could potentially surpass all other causes of mortality worldwide. The rise of AMR has created an urgent demand for novel antimicrobials. Traditional antibiotics are increasingly losing their efficacy, while the current pipeline for novel antibiotics remains inadequate to address this escalating threat (Muteeb *et al.,* 2023). The development of novel antimicrobials, coupled with sound policy and public awareness, is crucial to managing the AMR crisis and safeguarding global health (Coque *et al.,* 2023).

Marine-derived compounds have been found to be effective against drug-resistant pathogens, making them valuable candidates for developing new antibiotics and other therapeutic agents (Bharathi and Lee, 2024). These compounds, sourced from marine organisms such as sponges, algae, corals, mollusks, and bacteria, have shown significant potential in various therapeutic applications (Seedi *et al.,* 2025). Their biological activities include antimicrobial, antiviral, anticancer, anti-inflammatory, and antioxidant properties (Sithranga Boopathy and Kathiresan, 2010). Marine microbes are estimated to produce around 23,000 bioactive secondary metabolites. Among these, marine bacteria are particularly notable for their secondary metabolites, which exhibit a wide range of biological activities, including significant antimicrobial potential (Srinivasan *et al.,* 2021). Metabolites like (+)-aeroplysinin-1 from marine sponges have demonstrated activity against MRSA (Methicillin-resistant *Staphylococcus aureus*) (García *et al.,* 2016). The exploration and utilization of marine bioactive compounds not only contribute to the discovery of new drugs but also highlight the importance of preserving marine biodiversity. Sustainable practices in harvesting and utilizing these resources are essential to ensure the continued availability of these valuable compounds for future research and development (Ahmed *et al.,* 2024).

Kenyan coastal waters are a biodiversity hotspot, hosting a wide variety of marine species, including sponges, corals, algae, mollusks, and bacteria (Cowburn *et al.,* 2018). This diversity provides a wealth of bioactive compounds with potential applications in medicine, biotechnology, and environmental conservation. Marine organisms from Kenyan waters have been found to produce unique bioactive compounds with significant antimicrobial properties (Kaaria *et al.,* 2015; Wacira *et al.,* 2024). The research on marine-derived antimicrobials in Kenya is hindered by the limited number of comprehensive studies, often restricted to preliminary screenings without detailed characterization (Kariuki *et al.,* 2021). Advanced analytical techniques like GC-MS, NMR, and HPLC are lacking, which limits the full characterization and understanding of bioactive compounds (Kiani *et al.,* 2022). Collaborative efforts and increased investment in research infrastructure are needed to unlock the potential of Kenyan marine biodiversity in combating antimicrobial resistance (Endale *et al.,* 2023).

This review aims to highlight the importance of marine-derived bioactive compounds in addressing the global health challenge of AMR and to encourage further research and development in this field. Moreover, it emphasizes exploring the rich biodiversity of marine organisms found in Kenyan waters and their potential as sources of novel antimicrobial agents. The primary focus encompasses the identification, characterization, and evaluation of bioactive compounds derived from marine sponges, corals, seaweeds, fungi, and bacteria. Additionally, the review focuses on identifying study gaps and future directions, particularly concerning the understudied marine organisms in Kenya with potential antimicrobial activity.

Discussion

A global perspective of some antimicrobial compounds and their mechanism of action from marine organisms

Marine organisms represent a vast and largely untapped reservoir of bioactive compounds with potent antimicrobial properties (Srinivasan *et al.,* 2021). Given the rise of antibiotic resistance, the exploration of marine-derived antimicrobial agents has gained significant momentum (Beesoo *et al.,* 2017). These bioactive compounds have been found in a variety of marine life forms, including bacteria, fungi, sponges, algae, actinomycetes, mollusks, tunicates, sea cucumbers, and corals (Hussain *et al.,* 2023).

Marine sponges (porifera)

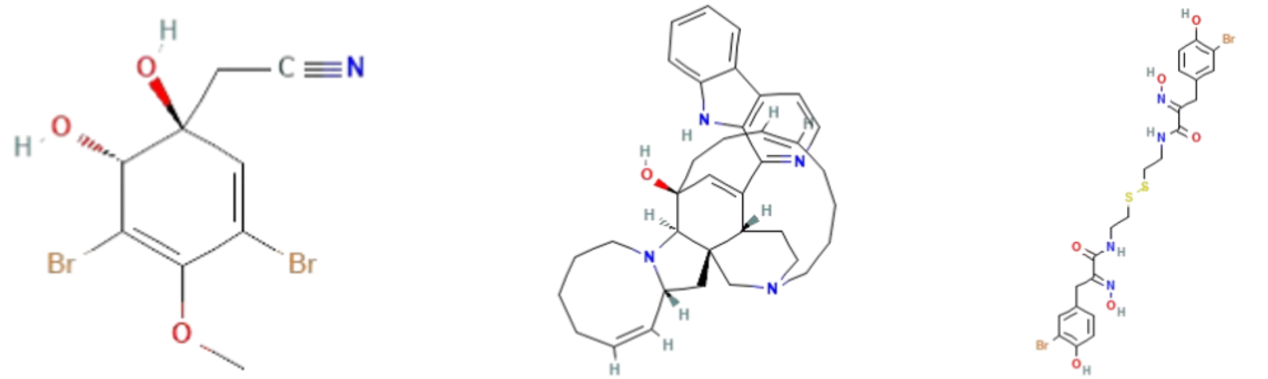
Marine sponges are known for their rich diversity of bioactive compounds. These compounds include alkaloids, terpenoids, and polyketides, which have shown promising antimicrobial, anticancer, and anti-inflammatory properties (Priya and Karthika, 2022).

Brominated alkaloids

Brominated alkaloids, such as bromotyrosines like Aeroplysinin-1, are bioactive compounds derived from marine sponges (Lever *et al.,* 2022) (Fig. 1). These compounds feature a unique chemical structure containing brominated phenol and tyrosine derivatives, which contribute to their potent antimicrobial properties (Patra, 2012). Bromotyrosines have been reported to demonstrate significant inhibitory effects against pathogenic bacteria, including *Staphylococcus aureus, Escherichia coli,* and *Pseudomonas aeruginosa* (Ferreira Montenegro *et al.,* 2024). Their mechanism of action involves disrupting bacterial cell membranes and inhibiting protein synthesis, ultimately leading to microbial cell death (Baran *et al.,* 2023).

Manzamine alkaloids

Manzamine A is a polycyclic alkaloid with a highly complex fused ring system, making it structurally unique among marine-derived bioactive compounds (Wahba *et al.,* 2012) (Fig. 1). This potent antimicrobial agent has demonstrated remarkable effectiveness against *Plasmodium falciparum*, *Mycobacterium tuberculosis*, and methicillin-resistant *Staphylococcus aureus* (MRSA). Its mechanism of action involves interfering with microbial DNA replication, ultimately disrupting cellular processes essential for survival and proliferation (Odunitan *et al.,* 2024).



(a) Aeroplysinin-1 (b) Manzamine A (c) Psammaplin A

Figure 1. Chemical structures of bioactive compounds derived from marine sponges (Porifera).

Halogenated polyketides

Psammaplin A is a remarkable compound characterized by its unique chemical structure, which includes a disulfide bridge and halogen substitutions (Jing *et al.,* 2019)(Fig. 1). This compound is renowned for its antimicrobial properties, notably its ability to inhibit Gram-positive bacteria and fungi, including *Candida albicans* (Kang *et al.,* 2015). The mechanism of action of Psammaplin A involves functioning as a histone deacetylase inhibitor, thereby disrupting bacterial metabolism and curtailing their proliferation (Hillman, 2022).

However, despite these findings, there remains a significant gap in research. Few studies have delved into the microbial symbionts associated with these sponges, which could hold the key to understanding and harnessing their full antimicrobial potential. Further investigation into these symbiotic relationships is essential to unlock the broader pharmaceutical applications of marine sponges (Freitas *et al.,* 2023).

Marine algae and seaweeds

The exploration of seaweeds has been revealed to produce valuable bioactive compounds. Marine algae and seaweeds produce antimicrobial compounds such as polysaccharides, terpenes, and phenolics (Menaa *et al.,* 2021).

Sulfated polysaccharides

Fucoidan, a sulfated polysaccharide derived from *Sargassum* species, is known for its notable antimicrobial activity, particularly against *Vibrio cholerae* and *Helicobacter pylori* (Mensah *et al.,* 2023) (Fig. 2). The compound's chemical structure is characterized by sulfated fucose polymers, which play a crucial role in its bioactivity. The primary mechanism of action for fucoidan involves binding to bacterial cell walls, thereby disrupting adhesion and colonization processes (Ohmes *et al.,* 2022).

Phlorotannins

Eckol, a polyphenolic compound isolated from *Ecklonia* species, exhibits significant antimicrobial activity, particularly against Gram-positive bacteria and dermatophytic fungi (Besednova *et al.,* 2020) (Fig. 2). The chemical structure of eckol includes multiple hydroxyl groups, which play a crucial role in its bioactivity. Its primary mechanism of action involves disrupting bacterial membranes and inhibiting oxidative stress enzymes (Manandhar *et al.,* 2019).

Halogenated furanones

Rubrolide B, a compound characterized by its furanone ring system with halogen substitutions, demonstrates significant antimicrobial activity by blocking bacterial quorum sensing, particularly affecting *Pseudomonas aeruginosa* biofilms (Shariati *et al.,* 2024) (Fig. 2). Its mechanism of action involves inhibiting bacterial cell-cell communication and the expression of virulence factors. However, the current body of research has its limitations, as the number of analyzed species remains limited and there is a pressing need for detailed characterization of the compounds responsible for the observed antimicrobial activity (Danquah *et al.,* 2022).

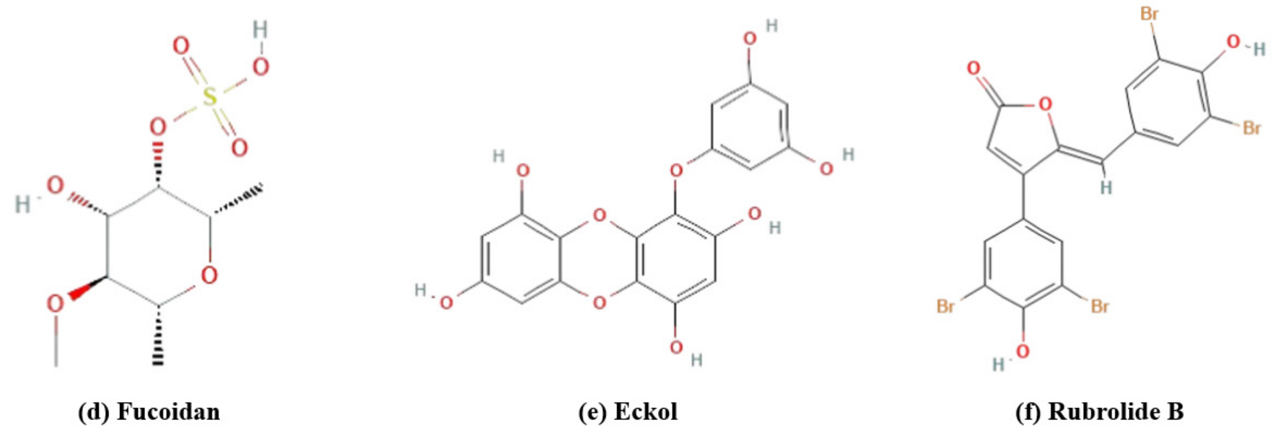
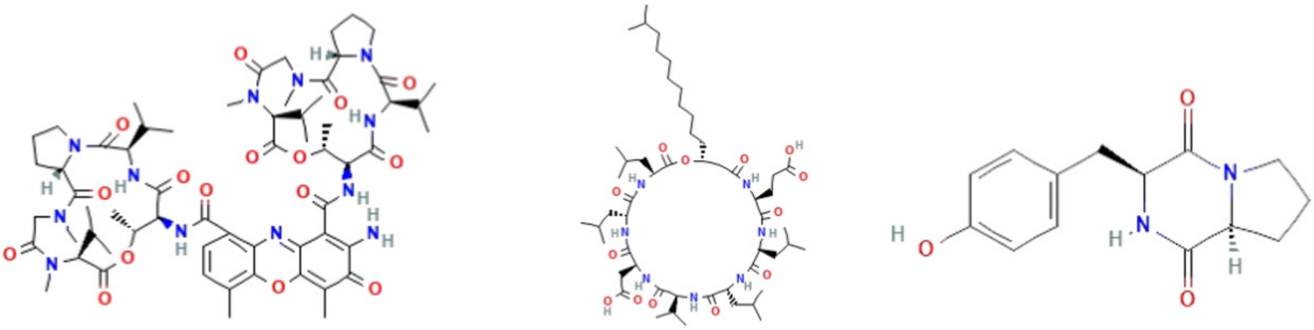


Figure 2. Chemical structures of bioactive compounds derived from marine algae and seaweeds.



(g) Dactinomycin (h) Surfactin (i) Maculosin-1

Figure 3. Chemical structures of bioactive compounds derived from marine bacteria and fungi.

Marine bacteria and fungi

Actinomycins

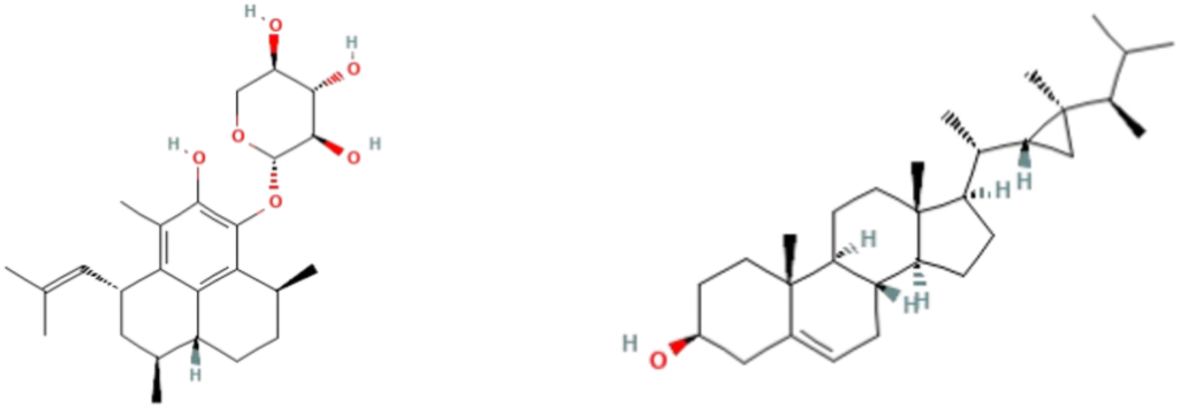
Actinomycin D, also known as dactinomycin, is a cyclic polypeptide derived from *Streptomyces* species (Djinni *et al.,* 2019) (Fig. 3). This compound features a distinctive phenoxazinone core within its chemical structure, contributing to its bioactivity. Actinomycin D exhibits significant antimicrobial activity against *Bacillus subtilis, Klebsiella pneumoniae*, and various drug-resistant fungi. Its primary mechanism of action involves binding to DNA, thereby inhibiting RNA polymerase activity and halting the transcription process (Sharma and Manhas, 2019).

Lipopeptides

Surfactin, a cyclic lipopeptide produced by *Bacillus* species, is characterized by its fatty acid tail and cyclic peptide structure (Théatre *et al.,* 2021) (Fig. 3). This compound exhibits significant antimicrobial activity, particularly against Gram-positive bacteria. The primary mechanism of action for surfactin involves forming pores in bacterial membranes, which leads to cell lysis and death. his highlights its potential as a valuable antimicrobial agent for various therapeutic applications (Tran *et al.,* 2022).

Diketopiperazines

Cyclo-(L-Pro-L-Tyr), also known as maculosin-1, is a cyclic dipeptide with aromatic substitutions derived from marine fungi (Bojarska *et al.,* 2021) (Fig. 3). This compound exhibits broad-spectrum antimicrobial activity against multidrug-resistant (MDR) bacteria. Its primary mechanism of action involves inhibiting bacterial protein synthesis and disrupting biofilm formation (Khameneh *et al.,* 2021).



(j) Pseudopterosin (k) Gorgosterol

Figure 4. Chemical structures of bioactive compounds derived from marine corals.

Coral-Derived Metabolites

Pseudopterosin, a diterpene glycoside isolated from soft corals, demonstrates significant antimicrobial activity, particularly against *Staphylococcus aureus* and *Candida albicans* (Tran *et al.,* 2022) (Fig. 4). Its chemical structure comprises a diterpene backbone linked to sugar moieties, which plays a crucial role in its bioactivity. The primary mechanism of action for pseudopterosin involves disrupting bacterial membrane integrity, leading to the inhibition of microbial growth and proliferation (Zhu *et al.,* 2024).

Sterols

Gorgosterol, a modified sterol derived from *Gorgonia* species, exhibits significant antimicrobial activity against Gram-negative bacteria and fungi (Hunt *et al.,* 2012) (Fig. 4). Its chemical structure includes side-chain alterations that differentiate it from other sterols. The primary mechanism of action for gorgosterol involves modulating membrane permeability, ultimately leading to cell death (Darnet *et al.,* 2021).

Overview of marine ecosystems along the Kenyan coastline

The Kenyan coastline stretches approximately 536 kilometers (333 miles) along the Indian Ocean. The marine ecosystems along the Kenyan coastline are diverse and dynamic, offering numerous ecological, economic, and cultural benefits. These ecosystems are interconnected and contribute to the overall health and resilience of the marine environment (Gesami and Nunoo, 2024). Conservation and sustainable management of these ecosystems are crucial to preserving their biodiversity and the services they provide to local communities and the global environment (Rasowo *et al.,* 2020).

Coral reefs

The Watamu Marine National Park, situated on the central coast of Kenya, is renowned for its rich biodiversity and vibrant coral reefs. This marine protected area features various coral species, including massive *Porites* colonies and balanced compositions of genera *Acropora* and *Pocillopora*. To the north, the Malindi Marine National Park, located in proximity to the town of Malindi, is an integral component of the larger Malindi-Watamu Marine National Reserve (Cowburn *et al.,* 2018). This Park is notable for its heterogeneous coral reefs, seagrass meadows, and mangrove ecosystems. In the vicinity of Mombasa, the Mombasa Marine National Park and Reserve is recognized for its renowned coral reefs, which provide habitat for a diverse array of marine fauna, including various fish species, sea turtles, and dolphins. On the southern coast, the Kisite-Mpunguti Marine National Park is distinguished for its pristine coral reefs and rich marine biodiversity, rendering it a preferred site for snorkeling and diving activities (Ransom and Mangi, 2010). These coral reef systems serve as essential ecosystems that support a diverse range of marine species and contribute significantly to the overall health of the oceanic environment. Additionally, they play a critical role in the livelihoods of local communities by facilitating fishing and tourism-related activities (Wambua *et al.,* 2021).

Seagrass meadows

Gazi Bay, located on the southern coast of Kenya, is renowned for its extensive seagrass meadows. These meadows are composed of various seagrass species, including *Thalassodendron ciliatum*, *Cymodocea rotundata*, and *Halophila ovalis* (Omollo *et al.,* 2022). Gazi Bay has become a significant site for seagrass research, especially in the context of carbon storage and ecosystem services (Githaiga *et al.,* 2017). Further along the southern coast, Diani Beach is another important location for seagrass meadows. The seagrass species found here include *Thalassia hemprichii* and *Syringodium isoetifolium* (Mwikamba *et al.,* 2024). These meadows provide critical habitats for marine life and contribute to the overall health of the coastal ecosystem. Nyali Beach, situated near Mombasa, is home to diverse seagrass meadows, with species such as *Enhalus acoroides* and *Halodule uninervis*. These meadows play a vital role in supporting marine biodiversity and protecting the coastline from erosion (Uku and Björk, 2005). Kanamai and Vipingo, areas along the Kenyan coast, also host significant seagrass meadows. The seagrass species found here include *Zostera capensis* and *Halophila stipulacea*. These meadows are essential for maintaining the ecological balance and providing habitats for various marine organisms. These seagrass meadows are vital ecosystems that support a wide range of marine species and contribute to the overall health of the ocean environment. They also play a crucial role in carbon sequestration, helping to mitigate climate change (Aboud and Kannah, 2017).

Mangrove forests

One of the most significant mangrove forests is found in Gazi Bay, located on the southern coast of Kenya. This area is renowned for its extensive mangrove coverage and has been the focus of numerous conservation and restoration projects (Aboud and Kannah, 2017). The mangroves in Gazi Bay include species such as *Avicennia marina, Rhizophora mucronata*, and *Ceriops tagal* (Neukermans *et al.,* 2008). Further along the coast, Mida Creek near Watamu is another important mangrove forest characterized by its rich biodiversity. It supports a variety of mangrove species, including *Bruguiera gymnorrhiza, Sonneratia alba*, and *Xylocarpus granatum* (Kairo *et al.,* 2002). Mida Creek is also a vital habitat for numerous bird species and marine life. Moving to the northern part of Kenya's coastline, the Lamu Archipelago is home to extensive mangrove forests. The mangroves in this region play a critical role in protecting the coastline from erosion and providing habitats for fish and other marine organisms (Kirui *et al.,* 2011). The dominant species in this area include *R. mucronata* and *A. marina*. The Tana River Delta is another significant location for mangrove forests in Kenya. The delta's mangroves are essential for maintaining the ecological balance of the region and supporting local communities' livelihoods (Gitau *et al.,* 2023). The species found here include *Ceriops tagal, Bruguiera gymnorrhiza*, and *Xylocarpus moluccensis (Okello et al., 2022)*. These mangrove forests are vital ecosystems that contribute to the overall health of the coastal environment in Kenya. They provide essential services such as coastal protection, habitat for marine life, and carbon sequestration, helping to mitigate climate change (Huxham *et al.,* 2015).

Sandy beaches and dunes

Diani Beach, located in Kwale County, is one of the most famous beaches in Kenya. Stretching about 17 km, it has been Africa's top beach destination for several years. The beach is characterized by its white sand, blue waters, and tall palm trees. Visitors can enjoy activities such as swimming, camel riding, and snorkeling (Ndivo and Waudo, 2012). Mambrui Beach, near Malindi, is known for its unique golden sand dunes formed by powerful ocean winds. This unspoiled natural beach is dotted with palm trees and is perfect for picnicking, swimming, and kitesurfing (Kimani *et al.,* 2017). Nyali Beach, situated near Mombasa, is another popular destination. It features soft white sand, clear blue and green waters, and gentle winds. The beach is ideal for swimming, sunbathing, and building sandcastles. Watamu Beach, located approximately 105 kilometers north of Mombasa, boasts pristine white sands and a vibrant marine park. The crystal-clear waters make it perfect for snorkeling and diving. These sandy beaches and dunes are not only beautiful but also play a crucial role in supporting local tourism and providing habitats for various marine species (Mwakumanya and Bdo, 2007).

Rocky shores

Kilifi Creek, located in Kilifi County, features rocky shores rich in marine biodiversity. The rocky outcrops and tidal pools provide habitats for various marine organisms, including crabs, mollusks, and sea urchins (Oyugi, 2007). Further South, near the border of Kenya, Shimoni is known for its rocky shores and coral reefs. This area is popular for snorkeling and diving, offering visitors a chance to explore the diverse marine life that inhabits the rocky crevices and coral formations (Mwadzombo *et al.,* 2023). Near Mombasa, the Mombasa Marine National Park and Reserve includes rocky shores that are home to a variety of marine species. The rocky coastline, combined with coral reefs and seagrass beds, creates a rich and diverse marine ecosystem. North of Mombasa, the Watamu Marine National Park features rocky shores and coral reefs. These rocky areas provide habitats for numerous marine organisms and are popular spots for snorkeling and diving. These rocky shores are vital ecosystems that support a wide range of marine species and contribute to the overall health of the coastal environment in Kenya. They also offer unique opportunities for marine exploration and recreation (Cowburn *et al.,* 2018).

Estuaries and lagoons

Estuaries and lagoons that play a crucial role in supporting marine biodiversity and local communities. One of the most significant estuaries is the Tana River Delta, located in the northern part of Kenya's coastline. This estuary is formed by the Tana River, the longest river in Kenya, as it empties into the Indian Ocean (Kitheka and Mavuti, 2016). The Tana River Delta is a vital habitat for various bird species, fish, and other wildlife. It also supports local communities through fishing and agriculture. Another important estuary is the Sabaki River Estuary, also known as the Athi-Galana-Sabaki River Estuary. This estuary is located near Malindi, where the Sabaki River meets the Indian Ocean (Thoya *et al.,* 2022). The Sabaki Estuary is characterized by its mangrove forests, sandbanks, and freshwater pools. It is an essential habitat for fish, birds, and other marine life, and it plays a significant role in supporting local livelihoods. In addition to estuaries, Kenya also has notable lagoons, such as the Mida Creek Lagoon (Okuku *et al.,* 2022). Located near Watamu, Mida Creek is a tidal lagoon surrounded by mangrove forests. It is a biodiversity hotspot, providing habitats for various marine species, including fish, crabs, and birds. The lagoon is also a popular destination for eco-tourism activities such as bird watching and kayaking. These estuaries and lagoons are vital ecosystems that contribute to the overall health of the coastal environment in Kenya. They provide essential services such as habitat for marine life, coastal protection, and support for local communities through fishing and tourism activities (Cowburn *et al.,* 2018).

Open ocean

The open ocean, also known as the pelagic zone, is characterized by its deep waters and is home to a wide variety of marine life, including large fish, marine mammals, and seabirds. The open ocean off the coast of Kenya is part of the Western Indian Ocean, which is known for its rich biodiversity and productive fishing grounds (Groeneveld, 2015). This region is influenced by the East African Coastal Current, which brings nutrient-rich waters from the south, supporting a diverse range of marine species. The open ocean in this area is also important for various economic activities, including commercial fishing, shipping, and tourism. Additionally, it plays a crucial role in regulating the climate by absorbing carbon dioxide and heat from the atmosphere (Gesami and Nunoo, 2024).

Previous studies on Kenyan marine organisms and their bioactivity

Previous studies on Kenyan marine organisms have demonstrated the immense potential of these organisms as sources of bioactive compounds. The research highlights the importance of conserving marine ecosystems and promoting sustainable use of marine resources. Continued exploration and study of Kenyan marine biodiversity can lead to the discovery of novel bioactive agents with significant therapeutic applications (Karthikeyan *et al.,* 2022).

Seaweeds (marine algae)

A study by Kaaria *et al.* investigated the antimicrobial potential of endophytic fungi from marine algae in Kibuyuni, Kenya, and found significant antimicrobial properties in several strains (Kaaria *et al.,* 2015). Similarly, another study along the Kenyan coast collected marine algae and isolated 3,493 bacterial strains. Twenty percent of these isolates showed inhibitory effects against at least one pathogen, with 69 strains displaying broad-spectrum antimicrobial activity. The study also revealed that Gram-positive bacteria were more susceptible to these isolates than Gram-negative bacteria. Additionally, it was noted that geographical location influenced the antimicrobial efficacy of the isolates (Kaaria *et al.,* 2015).

Marine sponges

A pivotal study focused on the sponge *Axinella infundibuliformis*, collected from the Kenyan coast, aimed to evaluate its antimicrobial potential. Researchers extracted various compounds from this sponge and assessed their activity against a range of microbial pathogens. The findings revealed that certain extracts exhibited pronounced antimicrobial effects, particularly against Gram-positive bacteria such as *Staphylococcus aureus* and *Bacillus subtilis*. Additionally, some extracts demonstrated activity against fungal pathogens, including *Candida albicans*. These results underscore the potential of *A. infundibuliformis* as a source of novel antimicrobial agents (Lutta *et al.,* 2008).

Additionally, earlier research presented at the 1st International Congress of the Federation of African Societies of Biochemistry and Molecular Biology in 1996 highlighted the antimicrobial and antifungal activities of selected marine algae and sponges along the Kenyan coast. While specific sponge species were not detailed, the findings underscored the potential of marine sponges in this region as sources of bioactive compounds (Titanji, 2005).

Marine-derived endophytic fungi

Wacira *et al.* in Kenya conducted a study on mangrove endophytic fungi, examining their antibacterial properties. Mangrove species from different locations were collected and their fungal isolates were affiliated to the *Aspergillus* genus. The fungal extracts were tested for antibacterial activity against *E. coli, S. aureus*, and *P, aeruginosa* using the disc diffusion method. The results indicated that *A. marina* and *R. mucronata* had the highest number of fungal endophytes with significant antibacterial activity, even surpassing positive controls (Wacira *et al.,* 2024).

Coral reef-associated microorganisms

A research study assessed the impact of anthropogenic activities on coral reef-associated microorganisms along the Kenyan coast. The study utilized metagenomic approaches to analyze the microbial community structure and functional potential. The findings indicated that coral reefs affected by human activities had distinct microbial communities with unique bioactive properties (Wambua *et al.,* 2021).

Comparative analysis of bioactivity research on marine organisms in Kenyan waters versus global trends

When comparing the research on Kenyan marine organisms to global trends, it becomes evident that while significant progress has been made, there are still gaps to be addressed. Globally, marine-derived antimicrobial compounds have been extensively studied, with numerous compounds identified from various marine organisms such as sponges, corals, and bacteria (Bharathi and Lee, 2024). These studies have led to the discovery of compounds with potent antimicrobial, antifungal, and anticancer properties. In contrast, research in Kenya has primarily focused on a limited number of species and has not yet reached the same level of comprehensive analysis. While Kenyan studies have identified promising antimicrobial compounds, the scope and depth of research are not as extensive as those conducted in other regions (Sohaili *et al.,* 2024).

Analytical Techniques for Identifying Antimicrobial Compounds

Identifying antimicrobial compounds from marine organisms involves several advanced analytical techniques, each with its unique strengths and applications. One of the most widely used techniques is Gas Chromatography-Mass Spectrometry (GC-MS) (Franco *et al.,* 2019). GC-MS combines the features of gas-liquid chromatography and mass spectrometry to identify different substances within a test sample. This technique is particularly effective for analyzing volatile and semi-volatile compounds. The process involves vaporizing the sample and then separating the components based on their mass-to-charge ratio. GC-MS is highly sensitive and can detect even trace amounts of compounds, making it invaluable for identifying antimicrobial agents in complex mixtures (Sinha *et al.,* 2023).

Nuclear Magnetic Resonance (NMR) spectroscopy is used to determine the structure of organic compounds by observing the behavior of nuclei in a magnetic field. This technique provides detailed information about the molecular structure, dynamics, and environment of the compounds (Emwas *et al.,* 2020). NMR is particularly useful for identifying the specific arrangement of atoms within a molecule, which is essential for understanding the mechanism of action of antimicrobial compounds. It can also be used to study the interactions between antimicrobial agents and their targets, providing insights into their efficacy and potential side effects (Phyo *et al.,* 2021).

High-Performance Liquid Chromatography (HPLC) is another analytical technique used to separate, identify, and quantify each component in a mixture. HPLC is particularly effective for analyzing non-volatile and thermally unstable compounds (Schieppati *et al.,* 2021). The technique involves passing a liquid sample through a column packed with a solid adsorbent material. Different compounds in the sample move through the column at different rates, allowing them to be separated and identified. HPLC is highly versatile and can be used to analyze a wide range of antimicrobial compounds, from small molecules to large biomolecules (Badawy *et al.,* 2022).

Study Gaps and Future Directions

Limited number of comprehensive studies on marine-derived antimicrobials

One of the significant gaps in the research on marine-derived antimicrobials in Kenya is the limited number of comprehensive studies. Many studies have focused on preliminary screenings and have not progressed to detailed characterization and mechanism of action studies (Sohaili *et al.,* 2024). Additionally, there is a lack of advanced analytical techniques such as GC-MS, NMR, and HPLC in many Kenyan studies, which limits the ability to fully characterize and understand the bioactive compounds (Mungwari *et al.,* 2025). Furthermore, there is a need for more collaborative efforts and increased investment in research infrastructure to support the identification and development of novel antimicrobial agents from Kenyan marine organisms. Addressing these gaps will be crucial for unlocking the full potential of Kenyan marine biodiversity in the fight against antimicrobial resistance (Rasowo *et al.,* 2020).

By addressing these study gaps and leveraging advanced analytical techniques, researchers can more accurately identify and characterize antimicrobial compounds, leading to the development of more effective treatments for infectious diseases. However, overcoming the current limitations in Kenyan studies will be crucial for realizing the full potential of these techniques (Kariuki *et al.,* 2021).

Understudied marine organisms in Kenya for antimicrobial activity

Kenya's marine biodiversity is a treasure trove of potential antimicrobial agents, yet many marine organisms remain understudied (Kimani *et al.,* 2017). The rich marine ecosystem, including various species of algae, sponges, and other invertebrates, harbors microorganisms that produce secondary metabolites with antimicrobial properties (Srinivasan *et al.,* 2021). In Kenya, research has predominantly been on terrestrial organisms, creating a substantial gap in our knowledge of marine-derived antimicrobials. Future studies should focus on exploring marine organisms to discover new antimicrobial compounds that can tackle the escalating problem of antibiotic resistance (Endale *et al.,* 2023).

Need for bioprospecting and large-scale screening programs

Bioprospecting, the systematic exploration of natural resources for commercially valuable compounds, is crucial for discovering new drugs and other bioactive substances (Manam, 2023). In Kenya, there is a pressing need for large-scale screening programs to identify and evaluate the antimicrobial potential of marine organisms. Such programs would involve the collection and analysis of samples from diverse marine habitats, followed by rigorous screening for antimicrobial activity. This approach not only enhances the chances of discovering new antimicrobial agents but also promotes the sustainable use of marine biodiversity (Kairigo *et al.,* 2020).

Exploration of host-associated microbiomes in marine organisms

The microbiomes associated with marine organisms play a vital role in their health and ecological functions (Ma *et al.,* 2023). These host-associated microbiomes can produce bioactive compounds that contribute to the antimicrobial properties of their hosts. Despite their importance, the interactions between marine hosts and their microbiomes remain poorly understood (Diwan *et al.,* 2023). Future research should focus on elucidating these interactions to harness the full potential of marine microbiomes in antimicrobial drug discovery. Understanding how these microbiomes influence host health and resilience could lead to innovative strategies for managing marine resources and combating microbial infections (Kamel *et al.,* 2024).

Need for standardization in antimicrobial screening methods

The lack of standardized methods for antimicrobial screening poses a significant challenge in comparing and validating results across different studies. Standardization is essential to ensure the reliability and reproducibility of antimicrobial assays (Hossain, 2024). Researchers must adopt uniform protocols for sample collection, preparation, and testing to facilitate the comparison of data and the identification of promising antimicrobial agents. Establishing standardized methods will also enhance collaboration between research institutions and streamline the process of translating laboratory findings into clinical applications (Garcia *et al.,* 2022).

Industrial potential and pharmaceutical development of Kenyan marine bioactive compounds

Kenya's marine bioactive compounds hold immense industrial and pharmaceutical potential. These compounds, derived from marine organisms, have shown promise in various therapeutic applications, including antimicrobial potential (Kaaria *et al.,* 2015). The development of these bioactive compounds into commercially viable products requires a multidisciplinary approach involving marine biology, chemistry, pharmacology, and biotechnology (Ghosh *et al.,* 2022). By investing in research and development, Kenya can capitalize on its marine resources to create new pharmaceuticals and contribute to global health solutions. Additionally, fostering partnerships with the pharmaceutical industry can accelerate the commercialization of marine-derived bioactive compounds, benefiting both the economy and public health (Pereira and Cotas, 2024).

Addressing the study gaps and future directions outlined will significantly advance our understanding and utilization of Kenya's marine biodiversity for antimicrobial drug discovery. By prioritizing research on understudied marine organisms, implementing large-scale screening programs, exploring host-associated microbiomes, standardizing antimicrobial screening methods, and developing industrial applications, we can unlock the full potential of marine bioactive compounds and contribute to the fight against antimicrobial resistance (McCubbin *et al.,* 2021).

Conclusion and recommendations

Summary of key findings

The exploration of Kenya's marine organisms has revealed a vast, untapped reservoir of bioactive compounds with significant antimicrobial properties. The key findings highlight the rich biodiversity of marine species in Kenyan waters, many of which remain underexplored for their potential antimicrobial activities. The study has underscored the critical role of marine microorganisms, algae, sponges, and invertebrates in producing secondary metabolites that can combat antimicrobial resistance (AMR). Despite the promising discoveries, there is a clear need for more comprehensive and systematic research efforts to fully harness this potential.

Recommendations for future research and policy development

To bridge the existing knowledge gaps, it is imperative to implement large-scale bioprospecting and screening programs targeting the diverse marine habitats in Kenya. Future research should prioritize the identification and characterization of bioactive compounds from understudied marine species. Additionally, there is a pressing need to standardize antimicrobial screening methods to ensure consistency and reliability across different studies. Policymakers should support these initiatives by providing funding, infrastructure, and regulatory frameworks that promote sustainable bioprospecting and the conservation of marine biodiversity. Collaborative efforts between research institutions, government agencies, and local communities will be essential in driving these research and policy advancements.

Potential for collaboration with international institutions for marine drug discovery

The journey towards discovering new antimicrobial agents from Kenyan marine organisms can be significantly accelerated through international collaborations. Partnering with global research institutions and pharmaceutical companies can facilitate the exchange of knowledge, expertise, and resources. These collaborations can provide access to advanced technologies and methodologies, enhancing the efficiency and scope of bioprospecting efforts. Furthermore, international partnerships can help in the commercialization of marine bioactive compounds, translating laboratory findings into market-ready pharmaceutical products. By fostering these collaborations, Kenya can position itself as a key player in the global fight against antimicrobial resistance, while also contributing to the sustainable development of its marine resources.

In conclusion, the study of marine organisms in Kenyan waters holds immense promise for addressing the global challenge of antimicrobial resistance. By building on the key findings and implementing targeted research, policy, and collaborative strategies, we can unlock the full potential of this hidden treasure trove and make significant strides towards innovative and effective antimicrobial solutions.

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Genetic research: Global and Kenyan contextual comprehensive review of freshwater fish populations

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Abstract

Capture fisheries and aquaculture provide more than 15% of the animal protein intake for humans, highlighting their vital role in reducing poverty and promoting sustainable global development by aligning with the 2030 Agenda for Sustainable Development. Genetic studies play a crucial role in tracking evolutionary changes and assessing the genetic health of endangered fish populations. As of August 2022, the National Center for Biotechnology Information (NCBI) database contained a total of 865 fish genomes. With over 15,000 known species of freshwater fish, scientists are continuously investigating genetic variation to enhance biodiversity understanding, stock management, and conservation strategies for endangered species. Freshwater fish populations often evolve in isolation, influenced by geographic barriers and environmental factors like temperature, pH, and food availability, which can result in significant genetic differentiation. Genetic research in Kenya has focused on various aspects, such as genetic divergence and adaptation, species conservation, and population genetics. This review examines the current status of genetic research in freshwater fishes, evaluates the necessary infrastructure to support further studies, summarizes the areas already explored, identifies existing gaps, and proposes directions for future genetic research both globally and within the Kenyan context.

Keywords: freshwater fish genetics, environmental stressors, population genetics, next-generation sequencing

Introduction

Fish populations in freshwater ecosystems play a critical role in maintaining ecological balance through nutrient cycling and serving as integral components of aquatic food webs (Villéger *et al.,* 2017). They also influence the overall health and stability of aquatic habitats by helping regulate populations of other organisms (Lapointe *et al.,* 2014). Adaptations to these environments are reflected in both physiological and behavioral mechanisms that enhance survival in freshwater habitats (Blewett *et al.,* 2022). Furthermore, a significant proportion of freshwater fishes are endemic to specific ecosystems, making them especially vulnerable to environmental changes and anthropogenic pressures (Masoumi *et al.,* 2024). The combined threats of habitat degradation, pollution, and the introduction of invasive species, has made conservation efforts imperative (De Santis *et al.,* 2023).

Genetic studies not only help track evolutionary changes but also allow for the identification of cryptic species, the detection of inbreeding, and the assessment of genetic health in endangered populations (Theissinger *et al.,* 2023). Genetic techniques have been utilized to estimate effective population sizes, determine species and evolutionary significant units (ESUs), and assess molecular variation in endangered aquatic species of the desert Southwest, providing critical conservation insights (Willi *et al.,* 2022).

Recent research has revealed significant genetic divergence in species like *Sarcocheilichthys parvus*, with genetic isolation resulting in the development of distinct lineages and sub-lineages shaped by landscape evolution (Li *et al.,* 2023). Additionally, paleo-drainage connections, which historically linked water courses, have played a key role in shaping the genetic structure and population dynamics of these fish (Bruyn *et al.,* 2013). In the case of *Oreochromis mossambicus*, a species facing threats due to human activities such as overfishing and water management practices, genetic research has shown that population differentiation and reduced genetic diversity are key challenges for its survival (Mashaphu *et al.,* 2024). Understanding the genetic variability of species like *O. mossambicus* is essential for developing conservation strategies that promote genetic resilience.

In Kenya, freshwater ecosystems such as the Nile Basin, Lake Victoria, Tana River and Lake Turkana support a diverse array of fish species, many of which are crucial for the livelihoods of local communities (Nyingi *et al.,* 2013). However, these ecosystems are facing significant increasing threats, including overfishing, habitat destruction, and pollution (Muthoka *et al.,* 2024).

Genetic research in Kenya has focused on the population structure, species identification, and the impact of human activities on freshwater fish populations (Barasa *et al.,* 2014). For instance, genetic studies of the Lake Victoria haplochromine cichlids have revealed significant genetic differentiation, with species being genetically monophyletic across their geographic ranges (Nakamura *et al.,* 2021).

The genetic tools available today offer valuable insights into species differentiation, population dynamics, and the impact of environmental changes on freshwater fish populations (Gebremedhin *et al.,* 2021). As freshwater ecosystems continue to face increasing threats from human activities, the need for genetic research to inform conservation efforts is more important than ever (Albert *et al.,* 2021). Ensuring the long-term viability of freshwater fish populations requires not only an understanding of their genetic makeup but also the development of strategies that protect genetic diversity and restore natural habitats (Mashaphu *et al.,* 2024).

This review highlights the importance of genetic research in understanding the evolution, population dynamics, and adaptation of freshwater fish populations worldwide, with an emphasis on conserving genetic diversity for effective conservation. In Kenya, genetic studies have shed light on species differentiation, the impact of human activities, and the necessity of sustainable management practices to preserve freshwater biodiversity in key ecosystems like Lake Victoria and Lake Turkana.

Discussion

Overview of genetic research on freshwater fish populations

Genetic research on freshwater fish globally has provided crucial insights into species evolution, adaptation to various environmental stressors, and the dynamics of genetic diversity within fragmented ecosystems (Martinez *et al.,* 2018). Kenya's diverse freshwater ecosystems - ranging from the Great Rift Valley lakes to the rivers and wetlands - offer a unique setting for the study of freshwater fish genetics (Nyingi *et al.*, 2013). Lake Victoria, one of the world's largest freshwater lakes, hosts an extraordinary diversity of fish species, including *Mormyrus kannume*, *Protopterus aethiopicus*, various *Haplochromine* species, *Brycinus* spp., *Rastrineobola argentea* (commonly known as *omena*), *Labeo victorianus*, *Enteromius species*., and *Synodontis victorianus* (Vanina *et al.,* 2019).

Genetic divergence and adaptation of freshwater fishes

Freshwater fish populations often evolve in isolation due to geographic barriers like rivers, lakes, and mountains (van der Sleen and Albert, 2022). Genetic studies, especially those using molecular markers like mitochondrial DNA, microsatellites, and next-generation sequencing, provide insights into how populations diverge over time and adapt to local conditions (Wenne, 2023). For example, studies have shown how populations of the same species living in different watersheds can develop significant genetic differentiation due to variations in environmental factors, such as water temperature, pH, and food availability (Liao *et al.,* 2024).

Kenya's freshwater systems host several endemic fish species, particularly in the Rift Valley lakes like Lake Victoria, Lake Nakuru, and Lake Baringo (Omondi *et al.,* 2018). Genetic studies on these endemic species provide valuable insights into how they evolved in isolated environments and the genetic factors that enable their adaptation to unique conditions (Vidal and García-Marín, 2011). Research on the genetics of the Nile tilapia (*Oreochromis niloticus*) and the various cichlid species in Lake Victoria has shown significant genetic divergence between populations in different lakes and rivers, which are essential for developing conservation strategies (Tibihika *et al.,* 2020) (Fig. 1).

Genetic research helps in identifying critical populations that need protection and in understanding the impacts of invasive species on native fish populations, like the introduction of the Nile perch (*Lates niloticus*) into Lake Victoria, which has severely disrupted the native fish communities (Nyamweya *et al.,* 2023).

Figure 1. Nile tilapia *(Oreochromis niloticus*) from the upper River Nyando, Kenya (Coordinates: 0°13'17.7"S 35°15'27.5"E) (Source: Author)**.**

Impact of human activities on freshwater fishes

Human-induced activities, such as dam construction, water pollution, overfishing, and the introduction of invasive species, have profound impacts on freshwater fish genetics (Chen *et al.,* 2023). These activities can lead to genetic bottlenecks, reduced genetic diversity, and the loss of unique genetic traits critical for fish species adaptation (Martinez *et al.,* 2018). In Kenya, genetic studies have been instrumental in assessing the extent of population of isolation and fragmentation, shedding light on how these factors affect genetic diversity and adaptability (Sadler *et al.,* 2023).

Figure 2. Endangered cyprinid fish species *Labeo victorianus* from the lower River Nyando, Kenya (Coordinates: 0°10'28.3"S, 34°55'34.9"E) (Source: Author)**.**

Figure 3. *Barbus altinialis* from the upper River Nyando, Kenya (Source: Author)**.**

Genomic tools for understanding speciation processes in freshwater fish

Next-generation sequencing (NGS) technologies have significantly advanced our understanding of speciation processes in freshwater fish

Figure 4. *Clarias gariepinus* (African catfish) of Lake Victoria Basin, Kenya (Source: Okechi *et al.,* 2004).

(Mehinto *et al.,* 2012). By examining large genetic datasets, researchers can better distinguish between genetic differentiation driven by speciation versus spatial population structure (Hutama *et al.,* 2017). As Kenya's freshwater fisheries support the livelihoods of millions of people, genetic studies are also applied to improve fishery management practices (Obiero *et al.,* 2023). Genetic monitoring helps track fish populations, ensuring sustainable harvests and identifying the impacts of fishing on population structure (Seljestad *et al.,* 2024). Additionally, the genetic diversity of species like *Clarias gariepinus* (African catfish) (Figure 4) and *Cyprinus carpio* (common carp) in Kenyan rivers is crucial in ensuring healthy populations for aquaculture (Emam *et al.,* 2024).

Current status of genetic research in freshwater fishes

Genetic research on freshwater fish populations has advanced significantly globally, driven by advances in molecular techniques and a growing awareness of the importance of genetic diversity for conservation and sustainable management (Martinez *et al.,* 2018). Genetic research in freshwater fish in Kenya is still in its developmental stages compared to more established research fields (Obiero *et al.,* 2023). However, there have been notable efforts in the study of native fish species, population genetics, and the application of genetic tools to aquaculture and conservation (Sanda *et al.,* 2024). The Kenya Marine and Fisheries Research Institute (KMFRI) has made diverse contributions to genetic research on freshwater fish in Kenya, encompassing both basic and applied genetic studies (Obiero *et al.,* 2023).

Biodiversity and freshwater fish species delimitation

Advancements in molecular genetics, particularly DNA barcoding and genomic sequencing, have greatly enhanced our ability to differentiate closely related species and comprehend their genetic divergence (Ali *et al.,* 2020). These methodologies are also instrumental in resolving instances of cryptic speciation, where species that appear morphologically similar are genetically distinct (Fišer *et al.,* 2018). Genetic tools, such as mitochondrial DNA sequencing and microsatellites, have been used to assess genetic diversity within species such as native tilapiine populations and the endemic species in Lake Victoria (Tesfaye *et al.,* 2021).

One of the key areas of genetic research in Kenya has been the identification and classification of freshwater fish species (Barasa *et al.,* 2014). KMFRI has contributed to the identification and classification of native and introduced freshwater fish species in Kenyan water bodies (Obiero *et al.,* 2023). Studies have focused on understanding the genetic diversity within major fish species in Kenyan waters, such as the catfish species and native cichlids (Mwaura *et al.,* 2023). Mitochondrial DNA markers have been frequently used to examine phylogenetic relationships and to identify cryptic species, which are common in Kenyan freshwater fish populations (Schmidt *et al.,* 2017). However, a comprehensive genetic inventory of the entire fish fauna in Kenyan freshwater ecosystems is still lacking (Syanya *et al.,* 2023).

Population genetics and conservation within freshwater fishes

Population genetics focuses on the genetic structure, diversity, and evolutionary processes within fish populations, which are essential for assessing their health, adaptability, and long-term viability (Hohenlohe *et al.,* 2021). The genetic structure of fish populations in Kenya's freshwater systems, such as Lake Victoria, Lake Turkana, and the Tana River, has been an area of active research (Ndiwa *et al.,* 2014). Studies have shown significant genetic differentiation among populations of Nile tilapia, which has implications for their conservation and management (Geletu *et al.,* 2025). Research on the genetic consequences of overfishing and the introduction of non-native species has also provided insights into the impact of human activities on genetic diversity (Pukk *et al.,* 2013). Population genetics studies have revealed the impact of overfishing, habitat degradation, and introduction of non-native species on the genetic diversity of fish populations (Martinez *et al.,* 2018).

Aquaculture genetics and freshwater fisheries management

Studies have explored the genetic improvement of farmed species such as Nile tilapia and the introduction of genetically improved farmed fish strains (Barría *et al.,* 2023). However, research on the genetic impacts of farmed fish escapees and their interaction with wild populations is still limited (San Román *et al.,* 2025). Studies on the genetic improvement of tilapia strains for increased disease resistance, growth rates, and tolerance to environmental stressors have been conducted (Abaho *et al.,* 2025).

Tilapia farming, is a major sector in the economy (Emam *et al.,* 2024) and genetic research in this area has focused on improving the productivity and sustainability of fish farming (Munguti *et al.,* 2022). Scientists have also been involved in evaluating the genetic consequences of farmed fish escaping into wild populations, ensuring that the genetic integrity of wild fish populations is maintained (Diserud *et al.,* 2022).

Ecological and evolutionary studies on freshwater fish populations

Ecologically, freshwater fish play a key role in aquatic ecosystems, influencing trophic dynamics, nutrient cycling, and the structure of biological communities. These studies examine the relationships between fish populations and their habitats, including factors such as water quality, habitat availability, and competition with other species (Mamun and An, 2022).

Genetic research in Kenya has focused on understanding how freshwater fish populations adapt to these environmental stressors (Sanda *et al.,* 2024). For instance, studies have looked into how populations of Nile tilapia in different lakes exhibit genetic adaptations to varying salinity levels and environmental conditions (Ndiwa *et al.,* 2016). KMFRI has examined how freshwater fish populations adapt to varying environmental conditions, such as changes in water quality, temperature, and habitat structure (Oyugi *et al.,* 2014). These studies have focused on understanding the genetic basis of adaptive traits, which is critical for the sustainable management of fisheries in the face of climate change and pollution (Muringai *et al.,* 2022).

Infrastructure needs for genetic research in freshwater fisheries

Laboratory facilities for freshwater fisheries genetic research

The global genetic research is on understanding the genetic structure and diversity within freshwater fish populations (Manel *et al.,* 2020). With the use of molecular markers, such as mitochondrial DNA, microsatellites, and more recently NGS researchers have been able to reveal population dynamics, species differentiation, and the mechanisms of adaptation in freshwater environments (Wenne, 2023). These studies have shed light on how fish populations evolve in isolation due to geographic barriers like rivers, lakes, and mountains (van der Sleen and Albert, 2022).

To advance genetic research on freshwater fishes in Kenya, the development of specialized molecular biology laboratories is essential (Amoussou *et al.,* 2019). Currently, many Kenyan universities and research institutions lack the state-of-the-art facilities required for high-throughput fisheries genetic analysis. Laboratory spaces equipped for DNA extraction, PCR amplification, and DNA sequencing are necessary (Nguinkal *et al.,* 2024).

Freshwater fisheries genetic analysis equipment

Environmental monitoring equipment is fundamental to genetic research, providing critical context for fish genetic data by assessing habitat conditions (Yang *et al.,* 2024). Water quality monitoring systems measure key environmental variables such as temperature, pH, and pollutants, which can influence fish genetics and adaptation (Zhang *et al.,* 2024). Global Positioning System (GPS) devices are also used to map the locations of sampled fish populations, helping researchers correlate genetic data with specific environmental conditions or habitat types (Hebblewhite and Haydon, 2010).

Genetic research on freshwater fish relies on a diverse range of equipment at every stage of the process, from field sampling to advanced sequencing and data analysis (Cermakova *et al.,* 2023). Each tool plays an essential role in generating accurate genetic data, which is increasingly vital as freshwater fish populations face growing threats from habitat destruction, climate change, and overfishing (Bănăduc *et al.,* 2022). Advanced equipment not only informs conservation strategies but also supports sustainable management practices and the preservation of biodiversity in these crucial ecosystems (Niesenbaum, 2019). The journey of genetic research begins in the field, where sampling equipment such as nets, traps, and fishing gear are used to capture freshwater fish from their natural habitats (Yao *et al.,* 2022). Once the fish are collected, biological samples, such as fin clips, scales, or blood, are carefully stored in preservative solutions or frozen to prevent degradation. Proper field sampling is the first step in obtaining reliable data for further analysis (Oosting *et al.,* 2020).

Once the fish samples are collected, DNA extraction is the next critical step. Specialized equipment, such as centrifuges for isolating DNA, microcentrifuge tubes, and pipettes, are used to handle small volumes of genetic material (Formosa *et al.,* 2010). High-quality DNA extraction kits or automated DNA extraction systems are essential for ensuring a high yield of intact fish DNA, which is crucial for successful genetic analysis (Lutz *et al.,* 2023). Polymerase Chain Reaction (PCR) is a technique frequently employed to amplify specific DNA regions, such as mitochondrial DNA or microsatellites. Essential PCR equipment includes thermal cyclers or PCR machines, which regulate the heating and cooling cycles needed for DNA amplification. After amplification, gel electrophoresis systems are used to analyze the PCR products and verify the success of the amplification process (Ghannam and Varacallo, 2018).

NGS has revolutionized genetic research, enabling large-scale, high-throughput fish DNA sequencing at an unprecedented. NGS sequencers, such as those from Pacific Biosciences, Illumina or Oxford Nanopore, are capable of generating millions of DNA reads in a single run, allowing researchers to explore entire genomes or targeted gene regions with great precision (Satam *et al.,* 2023). Alongside these sequencers, bioinformatics tools and software are indispensable for managing the vast amounts of data generated, including aligning sequences, detecting genetic variants, and conducting fish population genetic analyses (Casas and Saborido, 2023). Genotyping and molecular marker analysis also play an important role in studying fish genetic variation. Automated DNA sequencers help determine the nucleotide sequence of specific genetic markers, while fragment analyzers quantify and visualize fish genetic patterns (Dudu *et al.,* 2015). Additionally, SNP genotyping platforms allow for in-depth analysis of genetic variation across thousands of loci, offering detailed insights into fish population genetics and evolutionary processes (Taillebois *et al.,* 2021).

As the amount of data produced by genetic research grows, bioinformatics tools and data storage systems become indispensable

(Saparov and Zech, 2025). High-performance computers and servers are essential for processing large genomic datasets, and secure data storage systems, such as cloud storage or local servers, ensure the integrity and accessibility of genetic data (Shih *et al.,* 2023). Bioinformatics software, such as STRUCTURE or PLINK, facilitates fish population genetic analyses and the visualization of genetic relationships (Solovieva and Sakai, 2023). In some cases, researchers may need to observe specific physical traits or genetic markers in fish tissues (Cuéllar *et al.,* 2016). This requires equipment such as microscopes for examining cellular structures and fluorescence imaging systems for visualizing genetic markers tagged with fluorescent dyes. These tools are particularly useful when studying gene expression or tracking fish genetic changes at the cellular level (Pradhan *et al.,* 2023).

Benchmarking and research capacity on freshwater fish populations

Global benchmarking of fisheries research standards

Benchmarking is essential for aligning fisheries research with international conservation goals, such as the United Nations Sustainable Development Goals (SDGs) and agreements such as the Convention on Biological Diversity (Stratoudakis *et al.,* 2015). It supports the development of internationally recognized frameworks for assessing fisheries sustainability, ensuring that research contributes to the conservation and sustainable use of aquatic resources (Savari *et al.,* 2024).

Kenya's research efforts in freshwater fish genetics are relatively nascent compared to global leaders in the field, such as the United States, Canada, and European countries *(Basiita et al.,* 2018). These countries have well-established research infrastructures and genetic databases for fish species, which Kenya can look to as benchmarks. For example, research institutions such as the Fish Genetics and Breeding Program in Canada have pioneered genetic improvement programs for aquaculture, which can serve as a model for Kenya (Houston *et al.,* 2022).

Fisheries genetic technology capacity in low-resource regions

While there has been substantial fish genetic technology progress in well-resourced regions, many countries in Asia, Africa, and Latin America still face significant capacity gaps. These gaps include limited access to state-of-the-art equipment, underdeveloped research infrastructures, and a lack of trained personnel (Obiero *et al.,* 2019). Capacity-building initiatives, including funding for infrastructure and partnerships with international institutions, are critical to bridging these gaps. While Kenya has made strides in the field of fisheries research, the country faces significant limitations in research infrastructure and resources. Institutions such as the KMFRI and the University of Nairobi have made important contributions to fish genetics research, but there is still a shortage of advanced sequencing facilities and bioinformatics tools (Munguti *et al.,* 2023). Limited funding for research projects further exacerbates this gap. Nevertheless, KMFRI's research output has contributed valuable insights into the genetic diversity of freshwater fish species, and with increased investment, the institute can become a leading force in genetic research for freshwater biodiversity and aquaculture in the region (Aloo *et al.,* 2017).

Fish genetic research - current status and way forward

Genetic research on freshwater fish populations has made significant strides globally, contributing to our understanding of biodiversity, evolution, adaptation, and the impacts of human activities on these vital ecosystems. However, despite the advances, there are still gaps in knowledge and areas where research is limited (De Santis *et al.,* 2023) .

In Kenya, genetic research on freshwater fish populations has made considerable progress, particularly due to the country's rich and diverse aquatic ecosystems, which include lakes, rivers, and wetlands. However, despite these advancements, significant gaps still remain, and more research is needed to fully understand the genetic dynamics of freshwater fish populations in Kenya (Masese *et al.,* 2020).

Completed research areas on freshwater fisheries genetic research

Understanding fish population structure and genetic divergence

Genetic research on freshwater fish has primarily focused on analyzing population structure across various aquatic habitats (Martinez *et al.,* 2018). Researchers have used molecular markers such as mitochondrial DNA, microsatellites, and more recently, NGS, to assess how populations are genetically differentiated across rivers, lakes, and other freshwater systems (Wenne, 2023). Studies have demonstrated that geographic isolation, such as barriers created by dams or natural features, can lead to significant fish genetic divergence (Kobayashi *et al.,* 2024). For instance, research on cichlids in African lakes has shed light on how these populations adapt to different environmental conditions, leading to speciation (Takahashi and Koblmüller, 2011).

Kenya's freshwater ecosystems, particularly in the Rift Valley and Lake Victoria, are home to a number of endemic fish species, many of which face threats from habitat loss, pollution, and overfishing. Genetic research has been conducted to understand the genetic structure and diversity of these species. For example, studies on the genetics of cichlid species in Lake Victoria and other Rift Valley lakes have provided valuable insights into their evolutionary history, population structure, and genetic divergence (Takeda *et al.,* 2013). The tilapiine species has also been extensively studied to understand population genetics and adaptability across different lakes in Kenya (Yongo *et al.,* 2021).

Freshwater fisheries genetic adaptation to environmental stressors

A substantial body of work has explored how freshwater fish populations adapt to environmental stressors such as pollution, temperature changes, and salinity fluctuations (Agarwal *et al.,* 2024). These studies have highlighted the role of genetic variation in enabling fish populations to cope with altered environmental conditions. Examples include genetic adaptations to high levels of pollutants, like heavy metals, and thermal adaptations in species living in warmer waters. This research has been key to understanding the mechanisms of survival in the face of climate change (Hamilton *et al.,* 2017).

Fisheries conservation and management

Genetic research has played a crucial role in conservation efforts for endangered freshwater fish species. Identifying genetically distinct populations and understanding their genetic diversity has helped prioritize conservation efforts (Kim *et al.,* 2023). For instance, studies on the fish genetic health of populations of species such as the Atlantic have provided important data for designing conservation strategies (Sanda *et al.,* 2024). Moreover, the impact of invasive species, like the Nile perch in Lake Victoria, has been studied to understand how they affect the genetic structure of native fish populations (Mwanja *et al.,* 2012).

Genetic research has played a crucial role in the conservation of endangered species, especially those affected by overfishing, invasive species, and environmental degradation (Hedrick and Hurt, 2012). Research has helped identify genetically distinct populations, and genetic diversity studies have been used to design conservation strategies to prevent the loss of fish genetic material through inbreeding (Robledo *et al.,* 2024).

Use of genomic tools for freshwater aquaculture

The application of genetic research in aquaculture has been significant, particularly in the breeding of freshwater fish for sustainable farming. Research on improving traits such as growth rate, disease resistance, and environmental tolerance through genetic selection has been widely conducted (Eknath and Hulata, 2009). This research has helped improve aquaculture productivity and sustainability, benefiting economies and food security globally.

In Kenya, aquaculture, particularly Nile tilapia farming, plays a significant role in food security and economic development (Munguti *et al.,* 2022). Genetic research has been applied to improve fish farming practices by studying the genetic diversity of farmed species. Research has also focused on breeding programs aimed at enhancing disease resistance, growth rates, and tolerance to environmental stressors (Gjedrem *et al.,* 2012). The KMFRI has been actively involved in studies that assess the genetic health of farmed tilapia populations, contributing to the sustainability and productivity of the aquaculture industry (Abwao *et al.,* 2023).

Several studies have been conducted on the population genetics of key fish species such as Nile tilapia, catfish, and native cichlids across Kenya's freshwater systems (Tibihika *et al.,* 2020). These studies have identified genetic differentiation among populations in different lakes and rivers, which is important for managing fish stocks and preventing overfishing. These genetic insights are essential for creating effective management policies to protect fish populations in the face of environmental pressures and human activities (Sadler *et al.,* 2023).

Next-Generation Sequencing (NGS) and Genome-Wide Studies on freshwater fish

The advent of NGS technologies has been transformative for genetic research on freshwater fish. NGS has enabled large-scale, high-throughput sequencing of genomes, allowing researchers to examine entire genomes or specific genetic regions with unprecedented precision (Satam *et al.,* 2023). This has advanced our understanding of species differentiation, gene flow, and evolutionary processes. Several freshwater fish species' complete or partial genomes have been sequenced, providing valuable information for both evolutionary biology and conservation (Yang *et al.,* 2020).

One of the key areas of research in Kenya has been the use of genetic tools for species identification and biodiversity assessment. Molecular markers like mitochondrial DNA and microsatellites have been utilized to assess the genetic diversity of fish populations in Kenya's freshwater ecosystems (Ahmed *et al.,* 2023). These studies have been crucial in identifying cryptic and freshwater fish species and in better understanding the distribution of genetic variation among native and introduced species (Arisuryanti *et al.,* 2019).

Unexplored research areas on fisheries genetic research

Comprehensive global fish genetic databases

While there have been significant studies on specific species, there is still no comprehensive, globally accessible database of genetic information for freshwater fish populations (Brosse *et al.,* 2013). Many freshwater fish species, especially those in under-researched regions, lack detailed genetic data. A global repository could help researchers and conservationists track genetic diversity, identify at-risk populations, and inform conservation management on a larger scale (Obiero *et al.,* 2023).

Despite the progress, there is still a lack of a comprehensive genetic inventory of the entire fish fauna in Kenya's freshwater ecosystems (Hickley *et al.,* 2015). While some species, especially commercially important ones like Nile tilapia, have been extensively studied, many species, particularly those in less-explored regions or with less economic significance, remain understudied (Tibihika *et al.,* 2023). A complete genetic inventory would help assess the overall biodiversity of Kenya's freshwater systems and aid in identifying species that are at risk of extinction due to genetic erosion or environmental factors (Ruppert *et al.,* 2019).

Long-term studies on fisheries genetic effects of climate change

While there have been studies on the immediate genetic impacts of environmental stressors, long-term studies assessing the genetic consequences of climate change on freshwater fish populations remain limited (Huang *et al.,* 2021). Understanding how shifting climates influence genetic diversity, gene flow, and adaptation in freshwater ecosystems over time is crucial, especially as climate change accelerates (Weiskopf *et al.,* 2020).

Climate change is expected to have significant effects on freshwater ecosystems, but there has been limited genetic research on how freshwater fish populations in Kenya are responding to climate change. Research is needed to examine how shifts in water temperature, rainfall patterns, and water quality might affect the genetic diversity and adaptability of freshwater fish (Ficke *et al.,* 2007). Long-term monitoring of genetic changes in fish populations in response to climate change will be essential for predicting future trends and developing effective management strategies (Moltó *et al.,* 2024).

Genetic research on understudied freshwater fish species and ecosystems

Despite progress, many freshwater fish species and ecosystems remain understudied genetically. Research has primarily focused on commercially important species, such as tilapia or salmon, while lesser-known species, especially those in remote or less-accessible regions, are often overlooked (Radinger *et al.,* 2023). Freshwater fish in biodiversity hotspots like the Amazon or Southeast Asia still lack sufficient genetic information, and more studies are needed to understand these species' genetic diversity and evolutionary history (Zieritz *et al.,* 2024).

While certain species, such as Nile tilapia, have received attention in terms of genomic research, many native fish species in Kenya, especially those in remote or under-explored lakes, remain poorly studied. Species like the catfish and endemic cichlids in isolated Rift Valley lakes have not been the subject of in-depth genomic research, and their potential for adaptation to local environmental conditions remains largely unknown (Stauffer *et al.,* 2022). Expanding genomic research to these understudied species could reveal important information for conservation efforts.

Comprehensive Effects of Human-Induced Fragmentation on freshwater fish populations

Although there has been research on the effects of habitat fragmentation on freshwater fish populations, comprehensive studies linking genetic data to the long-term consequences of human-induced fragmentation such as dam construction, water diversion, and pollution are still lacking (Pavlova *et al.,* 2017). The genetic impacts of these human activities need to be studied in more depth to understand their effects on gene flow, population viability, and overall biodiversity (Mimura *et al.,* 2017).

Although genetic research has focused on the effects of invasive species and overfishing, long-term studies on the genetic consequences of other human activities, such as dam construction and water diversion, are still lacking (Wang *et al.,* 2021). These activities have fragmented fish habitats and reduced gene flow, and their impact on the genetic diversity of fish populations needs to be studied in greater detail (Pavlova *et al.,* 2017). Understanding the genetic effects of these human-induced changes will be crucial for the sustainable management and conservation of fish populations in the future (Sonesson *et al.,* 2023).

Impact of fish genetic engineering in aquaculture

While there has been considerable genetic research in aquaculture aimed at improving farmed fish, there is a need for further studies on the ecological and genetic consequences of genetically modified fish in wild populations (Sanda *et al.,* 2024). The escape of genetically modified or selectively bred farmed fish into natural ecosystems could have long-term impacts on genetic diversity and local adaptation. More research is needed to assess the risks of farmed fish escaping into the wild and interbreeding with native populations (Bolstad *et al.,* 2021).

In Kenya, the practice of genetic improvement in aquaculture mainly focuses on selective breeding rather than genetic modification. Research institutions, such as the KMFRI, have engaged in studies on breeding more resilient strains of Nile tilapia (*Oreochromis niloticus*) and African catfish to enhance aquaculture productivity (Munguti *et al.,* 2022). These efforts are aimed at improving growth rates, disease resistance, and stress tolerance, particularly in regions prone to environmental challenges such as fluctuating water temperatures and poor water quality. However, genetic modification (GM) of fish, such as engineering fish to grow faster or tolerate harsher environmental conditions, has not yet been widely implemented in Kenya's aquaculture sector, although the potential for such practices in the future exists (Munguti *et al.,* 2014).

Integrating fish genetic data with ecological and environmental research

Genetic studies often focus on isolated factors, such as genetic markers or environmental stressors, without fully integrating ecological or environmental data. There is a need for more interdisciplinary research that combines genetic data with detailed environmental and ecological studies (Rousseau, 2024). Such research could provide a more comprehensive understanding of how freshwater fish populations adapt to both genetic and environmental challenges, especially in the context of human-induced changes to freshwater habitats.

In Kenya, much of the genetic research is conducted in isolation, without integrating ecological and environmental data. The interaction between genetic factors and ecological pressures is vital for understanding the resilience of fish populations (Terer *et al.,* 2012). For instance, how do environmental stressors like pollution or habitat loss interact with genetic traits to influence fish survival and reproduction? More research is needed that integrates genetic data with detailed ecological studies to provide a holistic understanding of fish population dynamics (Canosa and Bertucci, 2023).

Functional fish genomics and gene expression

While sequencing the genomes of freshwater fish species is an important step, there is less research on functional genomics studying how genes are expressed in different environmental conditions or life stages. Investigating gene expression can provide deeper insights into the physiological processes that underpin adaptation and resilience, particularly in response to environmental stressors like pollution or temperature changes (Nielsen and Pavey, 2010).

Functional genomics, which studies how genes are expressed in different environmental conditions, remains an underexplored area in Kenya. While there has been research on genetic markers and population structure, little is known about how environmental stressors (such as water quality, temperature changes, or pollution) influence gene expression in Kenyan freshwater fish species (Mackler and Lea, 2018). Research on functional genomics could provide valuable insights into how fish adapt to environmental challenges and improve conservation strategies in the face of climate change and habitat degradation (Grummer *et al.,* 2019).

Gene editing clustered regularly interspaced short palindromic repeats and CRISPR-associated protein 9 (CRISPR/Cas9)

Gene editing technologies like clustered regularly interspaced short palindromic repeats and CRISPR-associated protein 9 (CRISPR/Cas9) offer the possibility of directly modifying the DNA of freshwater fish to introduce or enhance desirable traits, such as enhanced disease resistance or faster growth rates (Yang et *al.,* 2024). The approach could also be used to correct genetic defects in wild populations or restore endangered species. While gene editing in fish is still a developing field, it holds great promise for improving the resilience and health of both wild and farmed populations (Ansori *et al.,* 2023).

Metagenomics and microbiome research

The study of fish microbiomes microorganisms living in or on fish will become increasingly important in understanding how genetics influences fish health, growth, and disease resistance (Kanika *et al.,* 2024). Metagenomics, the study of genetic material recovered directly from environmental samples, will allow researchers to identify beneficial microorganisms that could enhance fish welfare and improve disease resistance, particularly in aquaculture settings (Nogueira and Botelho, 2021).

The way forward on genetic research in the freshwater fish populations

Genetic research is rapidly evolving, particularly with the advent of NGS technologies, bioinformatics tools, and high-throughput systems. To fully leverage these advancements, significant investment in laboratory infrastructure and human capital is required, especially in regions where resources for such research are limited (Koboldt *et al.,* 2013). To move forward in advancing genetic research on freshwater fish populations globally, and specifically in the context of Kenya, there is a critical need to enhance infrastructure and investment in key areas (Munguti *et al.,* 2023).

Investment in laboratory infrastructure for fish genetic studies

The foundation of genetic research lies in having state of the art laboratory facilities equipped to handle complex genetic analyses (Donohue *et al.,* 2021). Globally, well-funded research institutions and sequencing centers have been able to generate vast amounts of genetic data that are shaping our understanding of biodiversity, species adaptation, and evolutionary processes (Hoban *et al.,* 2022). However, in many regions, including Kenya, the lack of adequate infrastructure limits the ability to conduct high quality research (Whalen *et al.,* 2014).

Establishing advanced sequencing laboratories equipped with NGS platforms will allow researchers to sequence the genomes of freshwater fish at a much higher throughput and lower cost than traditional methods (Domrazek and Jurka, 2024). These facilities would not only support local researchers but also provide access to international scientists who may lack access to such resources in their own countries. Bioinformatics infrastructure is equally important, as it provides the computational tools needed to process and analyze the large fish datasets generated by sequencing (Rana *et al.,* 2021). Investment in high-performance computing systems and bioinformatics software will ensure that data is efficiently processed, analyzed, and stored (Sànchez *et al.,* 2015).

In Kenya, this could be addressed by setting up a national genetic research center dedicated to freshwater fish. Such a center would centralize resources, streamline research efforts, and become a hub for knowledge sharing among universities, research institutions, and private sector stakeholders (Bezeng *et al.,* 2025). This would also foster collaborative research projects on both the national and international levels.

Training and capacity building on fish genetics

Investment in infrastructure must go hand in hand with training and capacity building for researchers. To support the growth of genetic research in freshwater fish, particularly in Kenya, local scientists need to be equipped with the knowledge and skills to use advanced genetic technologies (Munguti *et al.,* 2024). This includes training in sequencing, molecular techniques, data analysis, and bioinformatics.

International collaborations, academic partnerships, and exchanges can help build local capacity in Kenya. Furthermore, building expertise in local research institutions will ensure that Kenya can lead its own genetic research programs and contribute to global freshwater fish genetics research (Kombo and Mwangi, 2018). Capacity building should also extend to policy makers, to ensure that they understand the potential of genetic research and can support informed decision-making in the context of conservation and freshwater fisheries management (Kadykalo, 2022).

Funding for research projects on freshwater fishes

While robust infrastructure is crucial, consistent and sustained funding for research is equally important. Governments, international organizations, and private investors need to prioritize freshwater fish genetics research, recognizing its importance in biodiversity conservation, sustainable fisheries, and aquaculture (Nyamweya *et al.,* 2023). In Kenya, government funding, combined with international grants and private sector investment, should be directed towards research that explores how genetic techniques can help restore threatened fish populations, improve aquaculture practices, and ensure the sustainability of freshwater ecosystems (Munguti *et al.,* 2023).

In addition to providing direct funding for research, financial support should also be allocated to long-term monitoring projects that track changes in the genetic diversity of freshwater fish populations in response to environmental pressures, such as climate change, pollution, or the introduction of invasive species (Phiri *et al.,* 2023)

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Strengthening international collaboration on freshwater fisheries genetics

Global challenges like biodiversity loss and the sustainability of freshwater fish populations require coordinated efforts across borders. Strengthening international collaboration is vital to advancing genetic research, as the ecological threats faced by freshwater fish are often not confined by national boundaries (Wang *et al.,* 2024). Kenya, with its rich biodiversity and unique freshwater ecosystems, can play a key role in international research initiatives, especially in the African context (Okello *et al.,* 2024). Collaborative projects, partnerships with international research institutes, and participation in global scientific networks will ensure that Kenya remains at the forefront of genetic research on freshwater species.

Through international collaboration, Kenya can gain access to resources, knowledge, and technology that may not be available locally. Additionally, sharing data and research outcomes can help shape global conservation strategies and policies aimed at preserving freshwater biodiversity (Otieno, 2023). Collaborative efforts would also facilitate joint research programs on transboundary rivers and lakes, where multiple countries share the responsibility of preserving fish populations (Ndimele *et al.,* 2024).

Developing and implementing policies on fisheries genetic research

Regulatory frameworks should be put in place to address the potential risks associated with genetically modified organisms (GMOs) in aquaculture. For example, policies can ensure that genetically modified or selectively bred fish are securely contained within farming environments and do not escape into wild ecosystems, potentially threatening the genetic diversity of native fish populations (Robinson *et al.,* 2024).

Investment in infrastructure must be paired with sound policies that guide genetic research and its applications. Kenya needs to develop and implement policies that promote the responsible use of genetic technologies in aquaculture, conservation, and fisheries management. Policies must ensure that the genetic integrity of native fish populations is safeguarded, especially with regards to genetic modification and selective breeding (Lal *et al.,* 2024).

Conclusion and recommendations

In both global and Kenyan contexts, genetic research in freshwater fish is indispensable for biodiversity conservation, sustainable fisheries management, aquaculture improvement, and environmental monitoring. As freshwater ecosystems face increasing pressures from human activities and climate change, genetic tools provide critical insights into how fish populations evolve, adapt, and interact with their environments. For Kenya, in particular, leveraging genetic research can help protect the rich freshwater biodiversity in the Great Rift Valley lakes and rivers, improve the sustainability of aquaculture, and ensure that conservation efforts are based on scientifically sound data. Continued investment in genetic research will be essential to address these challenges and secure the future of freshwater fish populations worldwide.

Table 1. Key focus areas of genetic research on some freshwater fish species worldwide

Fish Species	Common Name	Family	Region	Key Focus of Genetic Research	Reference
Barbus altinialis	Ripon barbel	Cyprinidae	Lake Victoria, Africa	Impact of introduced species (e.g., L. niloticus), population genetics, and conservation strategies	(Chemoiwa *et al.*, 2013)
Brycinus nurse	Nurse Tetra	Characidae	Lake Victoria, Africa	Species identification, population genetics, and phylogenetic relationships	(Hamid *et al.*, 2020)
Clarias gariepinus	African Catfish	Clariidae	Africa, Asia	Genetic improvement for growth rates, disease resistance, and aquaculture productivity	(Kebtieneh *et al.*, 2024)
Cyprinus carpio	Common Carp	Cyprinidae	Europe, Asia	Genetic improvement for aquaculture, disease resistance, and adaptation to environmental stress	(Xu *et al.*, 2014)
Danio rerio	Zebrafish	Cyprinidae	Global (Lab-based)	Biomedical Research, model organism for human health research, Androgenesis and vaccination research	(Teame *et al.*, 2019)
Esox lucius	Northern Pike	Esocidae	North America, Europe	Phylogeography, genetic variation and population structure	(Skog *et al.*, 2014)
Gambusia affinis	Mosquitofish	Poeciliidae	North America, Global	Genetic diversity, resistance to environmental stress, and invasive species management	(Mer Mosharraf Hossain *et al.*, 2019)
Haplochromine sp.	East African cichlids	Cichlidae	Lake Victoria, Africa	Speciation, genetic diversity, and adaptation to environmental changes	(Takuno *et al.*, 2019)
Ictalurus punctatus	Channel Catfish	Ictaluridae	North America	Disease resistance, growth rate, genome mapping	(J. Wang *et al.*, 2024)
Labeo victorianus	Ningu	Cyprinidae	Lake Victoria, Africa	Genetic variation, population decline, and conservation efforts	(Chemoiwa *et al.*, 2013)
Lates calcarifer	Barramundi	Latidae	Australia, Southeast Asia	Population genetics, aquaculture breeding, and genetic adaptation to environmental factors	(Prasertlux *et al.*, 2024)
Micropterus salmoides	Largemouth Bass	Centrarchidae	North America and Asia	Population genetics, conservation genetics	(Wang *et al.*, 2019)
Mormyrus kannume	Elephant-snout	Mormyridae	Lake Victoria, Africa	Genetic variation, reproductive strategies, and impact of environmental changes	(M.EL-Mahdi, 2018)
Oncorhynchus mykiss	Rainbow Trout	Salmonidae	North America, Europe	Genetic diversity, breeding programs, disease resistance, and adaptation to various environments	(Miebach *et al.*, 2023)
Oreochromis niloticus	Nile Tilapia	Cichlidae	Africa, Asia, South America	Genetic variation, breeding programs, resistance to diseases, and growth traits	(Shoemaker *et al.*, 2022)
Perca fluviatilis	European Perch	Percidae	Europe	Genetic differentiation, environmental adaptation, and selective breeding for aquaculture	(Vanina *et al.*, 2019)
Protopterus aethiopicus	Marbled Lungfish	Cyprinidae	East Africa	Genetic diversity, habitat preferences, and ecological adaptation	(Garner *et al.*, 2006)
Rastrineobola argentea	Silver Cyprinid (Dagaa in Swahili: Omena in Luo)	Cyprinidae	Lake Victoria, Africa	Population genetics, food web interactions, and adaptation to eutrophic conditions	(Ahnelt *et al.*, 2016)
Rutilus rutilus	Roach	Cyprinidae	Austria, Lithuania, England and Wales	Genetic diversity, population dynamics	(Butkauskas *et al.*, 2023)
Salmo salar	Atlantic Salmon	Salmonidae	North Atlantic	Population structure, migratory patterns, genetic markers for selective breeding	(Houston and Macqueen, 2019)
Synodontis victorianus	Lake Victoria squeaker	Mochokidae	Lake Victoria, Africa	Genetic structure and population dynamics in response to habitat changes	(Iyiola *et al.*, 2018)

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Market analyses of fish from Lake Naivasha, Kenya to inform its fishery's management

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Abstract

Lack of a comprehensive market analysis and information about the Lake Naivasha fishery dynamics hampers the development of appropriate policies, and investment decisions, for resource management. Without a clear understanding of the market trends, value chains, and consumer preferences, stakeholders are unable to optimize economic returns, address market inefficiencies, and implement sustainable practices that promote both conservation and economic growth. The aim of this study was to conduct a market analysis of Lake Naivasha fisheries to inform management. Structured and semi structured questionnaires were used to capture various variables of the fish market. Primary data was collected at the five landing beaches and two major fish markets in Nakuru and Nairobi while secondary data was collected from the annual fishery bulletin. The study found that the fishery is dominated by *Cyprinus carpio* (47.3%), *Oreochromis niloticus* (46.4%), *Clarias gariepinus* (6.3%), with the fishers being the largest player in the fishery at (39.9%), fish traders (35.8%) and consumer (9.9%) and other ancillary players. Retailers played a significant role in the fishery by being the main distribution channel in the market at (38.3%), followed by wholesalers (23.3%) and fish mongers (19.3%). Tilapia is the most preferred fish species with a market share of 36%, catfish (31%) and common carp (30.3%). The major market destination for Lake Naivasha fish is Nairobi and Nakuru markets. Factors influencing market dynamics include demand/supply of the fish product, climatic variations, population growth and urbanization. The study recommends that for a viable and vibrant fish market, there is need to invest in infrastructure at the fish *bandas* and the markets, establishing a fish hatchery within the county to ensure continuous restocking and enhance the competitiveness of Beach Management Units and traders through training and facilitating market access.

Keywords: market analysis,consumption, distribution, opportunities, investment

Introduction

Lake Naivasha is a shallow endorheic freshwater lake lying at the highest elevation of the Kenyan Rift valley at 1,890 m above sea level. The lake supports a wide range of biodiversity including fish, birds, mammals, reptiles and other aquatic flora both in and around the lake. Lake Naivasha was declared a wetland of international importance in 1994 under the Ramsar Convention (LNRA, 1999) due to its unique biodiversity, coupled with threats from anthropogenic activities.

The lakes' resources have been treated as "open access" property, being exploited by each and every individual (both legally and illegally), according to their needs, and capacity (Kundu *et al.*, 2010). The dominance of the introduced species has transformed the fishery from subsistence into a commercialized artisanal fishery for domestic markets, based on three major species (Nile tilapia, Common carp and Catfish.) The main economic benefits derived from the fishery include food, employment and incomes.Trade in fish from Lake Naivasha is contributing a significant proportion of protein intake for the majority of lake basin inhabitats including those in major urban centres neighbouring the lake.

Growth in fish trade has brought about incomes while fish processing for export has provided employment opportunities for those involved directly and indirectly in the fisheries sector. There are thousands of people involved in the marketing and distribution of fish and fisheries products. There are also many ancilliary services that are heavily dependent on fish trade (soft drink manufacturers, ice makers, transporters, boat builders, net menders, petroleum product sellers and packaging materials) which have led to economic growth, increase in households' incomes and poverty reduction (Aura *et al.,* 2019).

The sustainability of Lake Naivasha fisheries is under threat due to multiple factors. These include overfishing, habitat degradation, introduction of alien and invasive species, climate change, and the potential impacts of large-scale development projects such as geothermal power generation (Kundu *et al.,* 2010). The increase in prices of Nile tilapia has prompted fishers to increase fishing effort in order to maximize opportunities. New entrants in the fishery have also joined the fishery resulting in overfishing activities. Declining stocks of the target fish species threaten the sustainability of the stocks for domestic trade and population growth that is solely dependent on the fishery. The undesirable harvesting methods threaten the fisheries and are bound to have far reaching effects if not checked. Lack of sound financial advice and banking knowledge have left the fisher community with a lot of disposal income and institutions particularly the cooperatives have failed (Manyala and Gitonga, 2008).

In recent years, the demand for fish from Lake Naivasha has been rising steadily, driven by population growth and urbanization in the surrounding areas. Ensuring sustainable management practices and informed decision-making in the sector is critical to prevent over exploitation and preserve the ecological balance of the lake while maximizing the socio-economic benefits derived from its fisheries resources (Abila, 2000). This technical report aims to provide a comprehensive market analysis of the fisheries sector in Lake Naivasha, with the aim of informing management, investment decisions, and policy making to ensure the long-term sustainability and socio- economic benefits of the industry.

The fisheries sector in Lake Naivasha faces significant challenges that require immediate attention and effective management strategies (Parry *et al.,* 2012). The lack of comprehensive market analysis and information about the industry's dynamic nature hampers the development of appropriate policies, investment decisions, and resource management practices. Without a clear understanding of the market trends, value chains, and consumer preferences, stakeholders are unable to optimize economic returns, address market inefficiencies, and implement sustainable practices that promote both conservation and economic growth.

The Lake Naivasha fisheries sector lacks up-to-date market information, which hampers effective decision-making for both investment and policy formulation. Without a comprehensive understanding of the market dynamics, it becomes difficult to identify potential investment opportunities, optimize the value chain, and implement sustainable management practices (Jones *et al.,* 2012; Tanner *et al.,* 2014; Shanguhyia, 2021). Therefore, a detailed market analysis is essential to bridge this knowledge gap and facilitate informed decision-making. The current study conducted a market analysis of Lake Naivasha fisheries to provide stakeholders with valuable insights and information for effective management decisions, investment options and policy formulation.

Materials and methods

Study area

Lake Naivasha is one of the shallow freshwater bodies in Kenya and the second largest after the gulf part of L. Victoria. The lake lies on the Eastern Rift Valley floor (0° 46′ S, 36° 20′ E) at about 1890 m above sea level. Its surface area varies between 110 and 160 km^2 during the dry and wet spells, respectively. There are five designated landing sites around the lake (Fig.1).

Study population

The study targeted fishers and traders at the five landing sites who eke their living from the fishery resource and are registered BMU members. So far there are 750 registered BMU members in Lake Naivasha cutting across the five landing sites. The study also targeted fish traders in Nakuru and Nairobi markets. Purposive sampling technique was used to ensure that each player in the market had an equal chance of filling out the questionnaire.

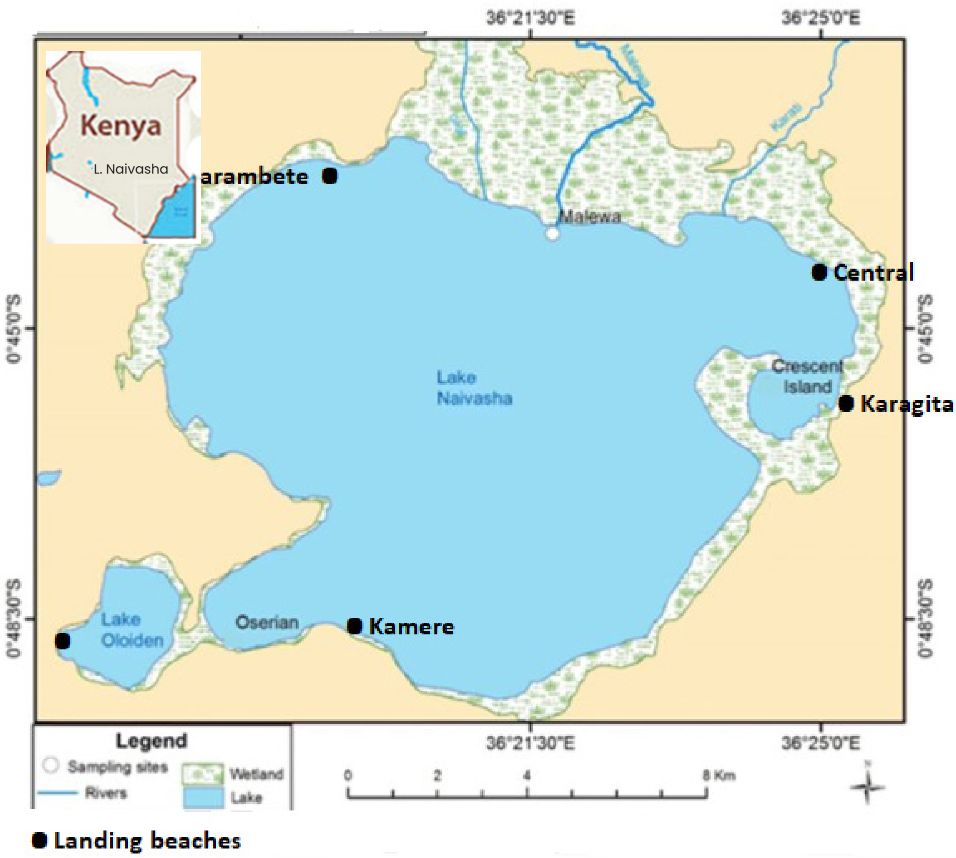

Figure 1. Fish landing beaches around Lake Naivasha where data was collected (Source: Authors)**.**

Sampling procedure and design

The study made use of questionnaires as the major tool for collecting primary data. Structured and semi-structured questionnaires capturing various variables were used. In this study, a total of 500 questionnaires were distributed at the five landings, out of which 400 questionnaires were filled and returned, representing an 80% response rate. According to Mugenda and Mugenda (2008), a 30% response rate is appropriate for analysis. The highest response was from Kamere landing beach (26.3%) followed by Central landing beach (25%), Karagita landing beach (25%), and Tarambete (23.8%). At the Nairobi main markets, 50 Questionnaires were administered while at the Nakuru top market, a total 35 administered and returned representing a response rate of (70%). A likert scale of 5.5 was used to allow for consistency and ease of answering. The collected data was thoroughly examined and checked for completeness and whether it was comprehensible.

Data collection

A survey was conducted by staff of Kenya Marine and Fisheries Research Institute, Naivasha station in November 2023. Data was collected at the five landing beaches around the lake namely: Central, Karagita, Kamere, Oloidien and Tarambete and the major fish markets in Nakuru and Nairobi which are major destinations for this fish.

Data analyses

Both qualitative and quantitative data analysis methods were used and the data keyed in MS Excel and organized neatly for ease of analysis. Data presentation was done using percentages, frequency tables, and figures for ease of reference and interpretation.

Results and discussion

Current state and trends of the Lake Naivasha fisheries market by volume, and value

The artisanal commercial fishery of Lake Naivasha is dependent on exotic species with introduction dating back from 1925 to 2011 for different purposes namely; *Oreochromis niloticus* (Nile tilapia), *Oreochromis leucostictus* (Blue spotted tilapia), *Coptodon zillii* (Redbelly tilapia), *Micropterus salmoides* (Largemouth bass), *Cyprinus carpio* (Common carp) and *Clarias gariepinus* (African sharptooth catfish). The riverine *Barbus amphigramma* and *Procambarus clarkii* (Red Louisiana Crayfish) have also been supporting the fishery significantly since 1980s. The Black lampeye was the only endemic species, but is now considered extinct. Two other species (*Barbus palundinosus* and *Oncorhyncus mykiss*) are natural riverine intruders

Earlier reports had estimated the potential annual fish production of Lake Naivasha at about 5000 metric tonnes/yr. However, the actual fish production realized over the last 40 years has been fluctuating between 37 metric tonnes and 3087 metric tonnes. The status of fish yield, fishing effort and catch per unit effort (CPUE) between 2013 and 2022 is summarized in figure 2.

Production of fish has been enhanced by fish stock re-introductions and restocking programs since 2011 through the economic stimulus program (ESP). Currently, there are five designated fish landing sites along the lake shore (Central, Karagita, Kamere, Tarambete and Oloidien) where daily statistics are recorded with an average annual yield of the lake being about 1625 metric tonnes. Gillnet fishing is the traditionally prescribed and gazetted method of fishing in Lake Naivasha. However, other fishing methods such as hook and line, longline and baited traps have also emerged.

Before the establishment of Nile tilapia population in Lake Naivasha, the value of fish landed from the fishery was less than KES 100 million (Fig. 3). However, between 2015 and 2021, the increasing trends in annual fish production parallels the rising value of fish during the period, with a minimum of KES 129.3 million and a maximum KES 409.5 million recorded during the period. These results reflect the importance and impacts of various management interventions made on the lake's fishery aimed at achieving the national objectives of Blue Economy.

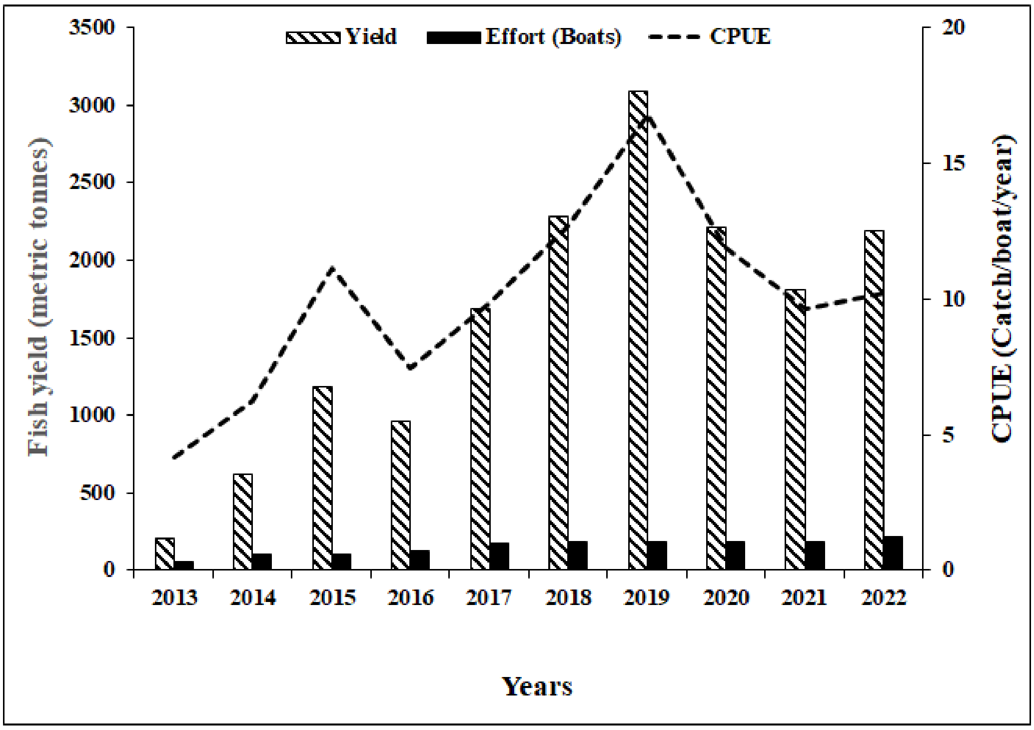

Figure 2. Status of fish yield, fishing effort and catch per unit effort (CPUE) in Lake Naivasha between 2013 and 2022. (Data source: KMFRI, KeFS and County Directorate of Fisheries).

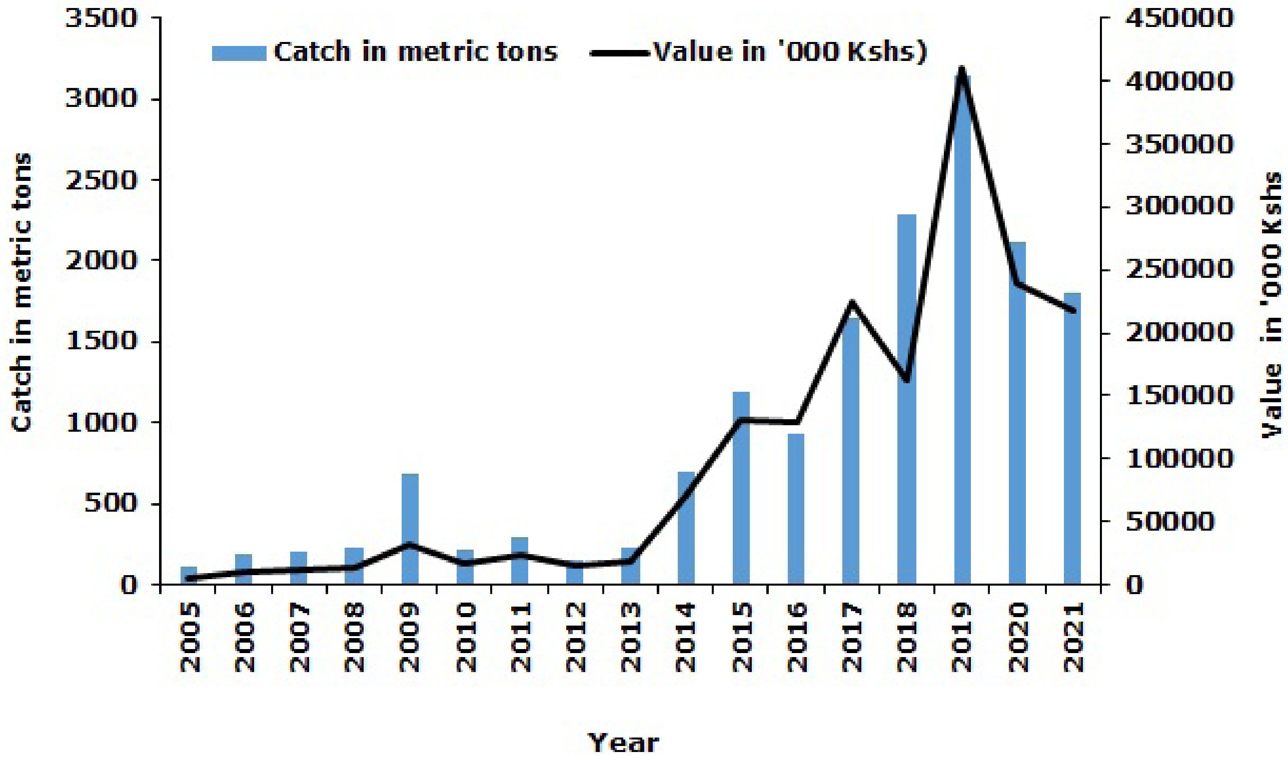

Figure 3. Trends in annual fish landings from Lake Naivasha fishery and value (2005-2021).

Nature of players in the fish market in the Lake Naivasha fisheries market

The Lake Naivasha fishery is characterized by a unique market structure with a dominant players comprising of the fishers (39.9%), fish traders (35.8%) consumers (9.9%), transporters (5.5) and other ancilliary players (Table 1). There also many ancilliary players that are heavily dependent on fish trade (soft drink distributors, ice makers, transporters, boat builders, net menders, petroleum product sellers and packaging materials) All of whom have spurred economic growth and contributed to an increase in households' incomes and poverty reduction.

Landing sites

The fishery is characterized by a large number of new entrants who have joined the sector in the last 5 years adding pressure to an already strained ecosystem and its sustainability (Table 2). This high number could be attributed to the high levels of unemployment in the country, rural –urban migration, the profitable nature of the trade, closure of many floricultural firms etc.

Table 1. Characteristics of respondents.

Occupation	Central	Kamere/ Oloidien	Karagita	Tarambete	%
Fisher	34	44.9	27.6	53.2	39.9
Fish trader	47	33.6	37.1	25.5	35.8
Fisheries Manager	1	1.9	1.0	1.1	1.2
Ancillary players	1	4.7	11.4	2.1	4.8
Transporter	5	0.9	8.6	7.4	5.5
Consumer	10	10.3	8.6	10.6	9.9
Processor	2	3.7	5.7	-	2.9
	100	100	100	100	100.0

Table 2. Number of years in the sector.

Years	% Respondents
<5	37.7
5_9	29.0
10_14	18.7
15_19	4.6
>20	10
	100

The study found that the average weight of fish sold per day per trader (29.9%) was 20 kg, followed by 7.5 kg (27.8%) of the traders, while (26.1%) of the traders were selling more than 30 kg day^{-1}. This is indicative of the huge demand and ready market for the fish and fishery from Lake Naivasha and the rising demand for white meat (Table 3).

Table 3. Average weight of fish sold per day.

Unit classes (kg)	% Respondents
<5	16.2
5_10	27.8
10_30	29.9
>30	26.1
	100

Contribution of various fish species

The fishery is primarily dominated by *C. carpio* (47.3%), *O. niloticus* (46.4%), *C. gariepinus* (6.3%). Species which previously dominated the fishery (*O. leucostictus, C. zilli, M. salmoides*) have contributed dismally to the total landings in Lake Naivasha. (Table 4). This situation can be attributed to factors such as fish species introductions, effect of overfishing and changes in the habitat condition within the lake (Njiru *et al.*, 2017; Waithaka *et al.*, 2019; Morara *et al.*, 2022).

Table 4. Percentage composition of fish landings from Lake Naivasha.

Species	Percentage composition (%)
M. salmoides	0.01
C. gariepinus	6.28
O. niloticus	46.42
Tilapia others	0.01
C. carpio	47.29
Total	100.00

The study established that tilapia was the most preferred species at (36%), Catfish (31%) common carp (30.3%) as shown in figure 4. The respondents extended the notion that tilapia fish is tasty and has high market demand and high economic returns.

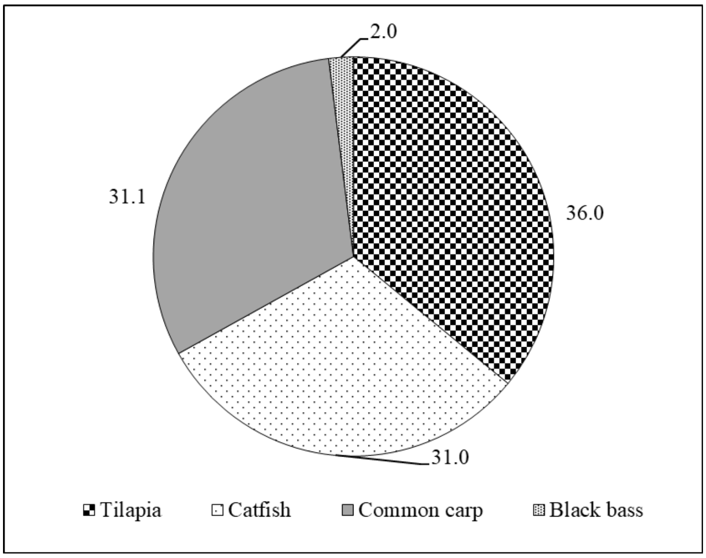

Figure 4. Most preferred fish in Lake Naivasha.

The study found that some of the factors affecting market dynamics include demand/supply of the product, climatic variations, population growth, urbanization, Competition for the resource and infrastructural limitations which affect the market trends and pricing (Fig. 5).

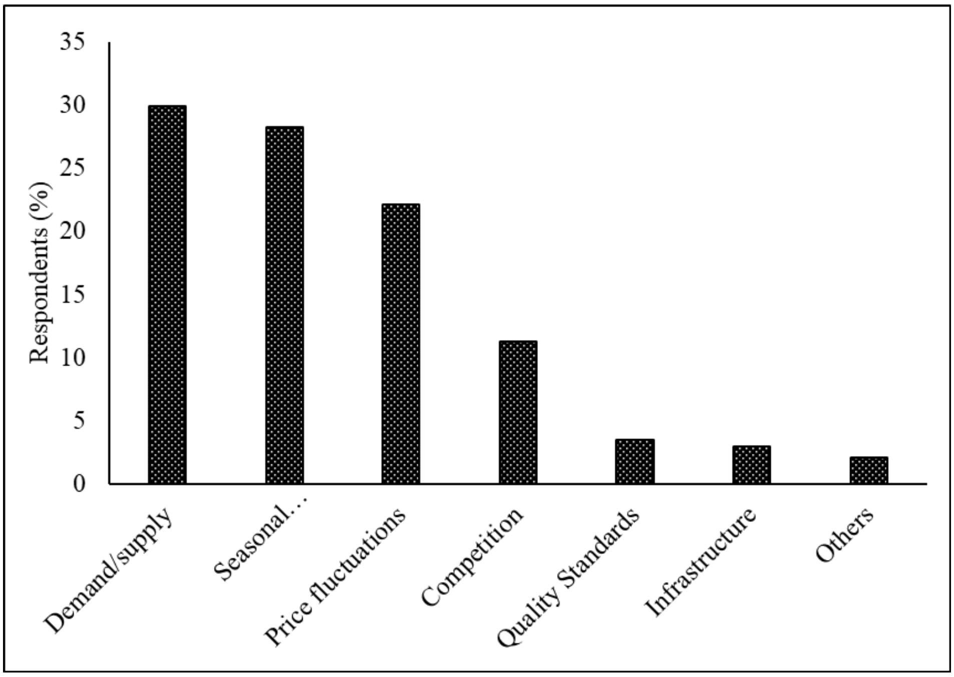

Figure 5. Factors affecting market dynamics of fish.

Current market distribution channels

Lake Naivasha fish market is controlled by a few individual players who have established themselves as almost monopolistic forces, exerting control over the market dynamics and pricing. The dominant players in the market distribution channels include retailers (38.3%), wholesalers (23.3%), fish mongers (19.3%) and the rest respectively (Table 5). The wholesalers act like middlemen between the fishermen and the retailers and fish mongers. The dominance of this few powerful players has significant implications for market dynamics. Their control over capital, and distribution channels gives them an advantage in terms of pricing, market access, and market influence.

Table 5. Main players in the fish market in Lake Naivasha.

Market player	% Respondents
Wholesalers	23.3
Restaurants	7.8
Retail	38.3
Fish mongers	19.3
Others	11.2

Small-scale traders provide an opportunity for market diversification and wider market reach. Their role in distributing of fish to various towns and facilitating regional trade contributes to food security, income generation, guaranteed livelihoods and economic development. Small scale traders (63.8%), long distance traders (32.8%) cover regions beyond the county at and the rest, respectively (Table 6).

Table 6. Key distribution channels in the region.

Channels	% Respondents
Small traders	63.8
Export traders	1.7
Long distance traders	32.8
Others	1.7
	100

This study established that fish harvested in Lake Naivasha is sold fresh at the five landing sites with a larger proportion being transported to market destinations like Gikomba and City Market in Nairobi, Top Market in Nakuru and Narok Main Market. Processed (deep fried) fish are destined for distance markets like Busia, Homabay among others (Fig. 6).

Challenges in the Lake Naivasha fisheries market

Challenges experienced included low supply of fish as a result of low catch, theft of fishing gears and catch, rampant illegal unreported and unregulated fishing (IUU)and low demand for non-target fish species. These need to be addressed to enhance the sustainable exploitation of the resource and maximize the socio-economic benefits for local communities.

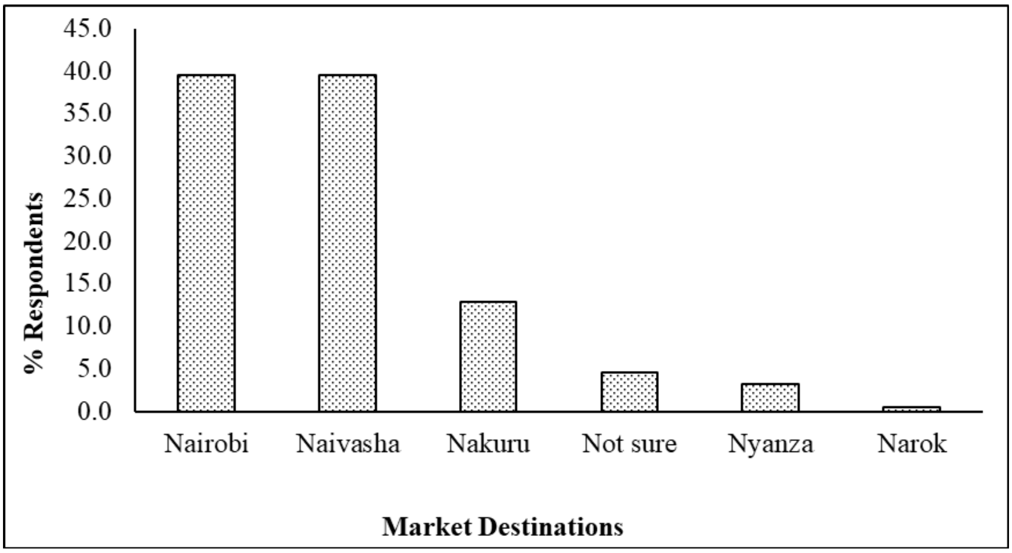

Figure 6. Market destinations of Lake Naivasha fish.

Fish sourced from L. Nakuru, which was banned is illegally harvested and floods the markets in the county. This affects the pricing of fish in the market due to the high supply and low demand effect. The fish is also mostly larger in size than the tilapia fish caught from Lake Naivasha, hence unsuspecting consumers end up purchasing it at a lower price, affecting the pricing of fish from Lake Naivasha in the market (Fig. 7).

Opportunities in Lake Naivasha fisheries market

Investing in infrastructure improvement at the fish bandas' and the markets (cold storage chain, transportation network and internet and other market infrastructure) are key opportunities. Establishing a hatchery for fingerling production within the county to enable restocking of the lake at a reasonable cost, and enhance the competitiveness of BMUs and traders through training and facilitating market access. Implementing and promoting regulations that promote fair competition, transparency, and market access for all market participants (Table 7). Providing training and support to fishers in areas such as value addition, business management, financial literacy, and market intelligence to facilitate market access for the fish traders is an area to be looked into and can help fishers and traders navigate market challenges more effectively.

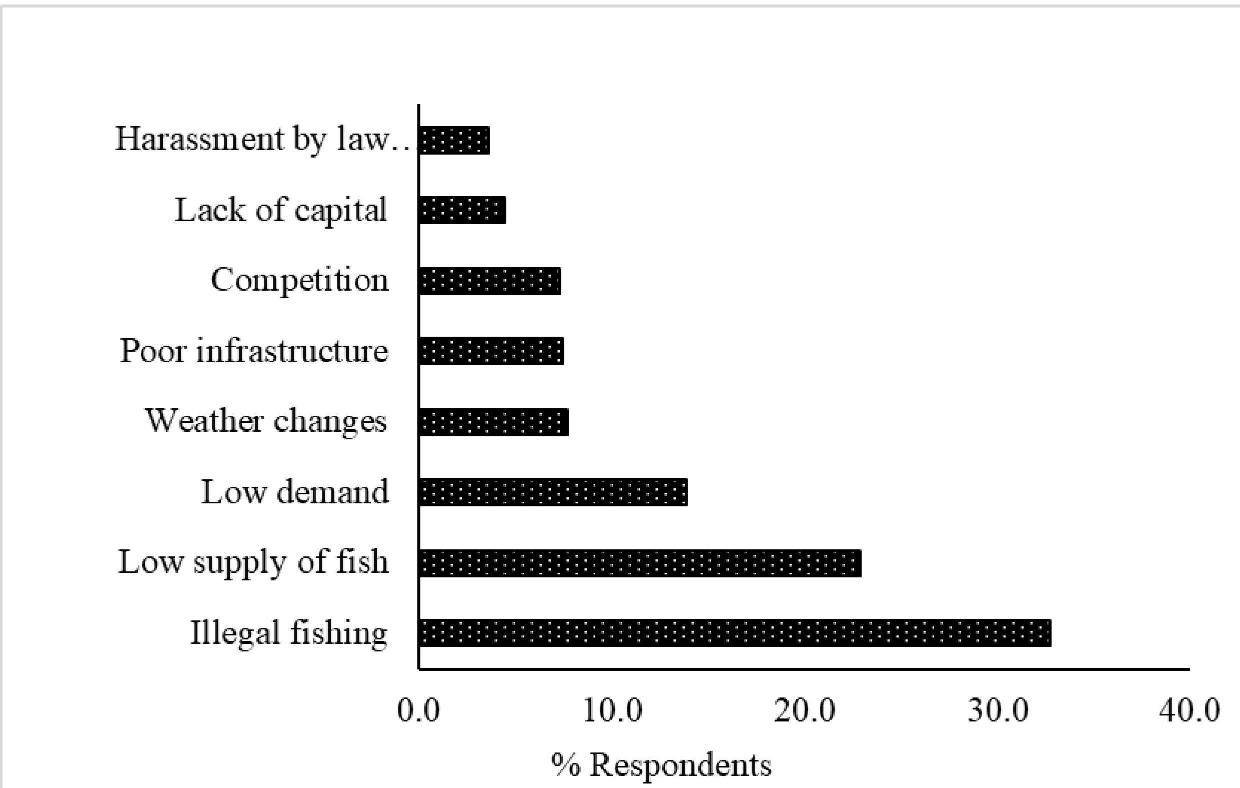

Figure 7. Cited challenges by respondents.

Table 7. Opportunities in the fish market

Opportunities	% Respondents
Value addition	17.6
Construction of cold storage	9.9
Ecotourism	6.5
Hatchery	10.8
No idea	41.4
Improvement of infrastructure	11.1
Mobile banking	2.8

Measures to improve marketing and management of the industry

The study recommends that improvement of the following measures will improve the marketing of the fish from Lake Naivasha and strengthen the management of the resource. Some of the measures cited include strengthening monitoring control and surveillance, restocking and improvement of market infrastructure (Fig.7).

Strategies for investment and policy

Figure 8 shows some of the strategies and policies suggested by the respondents. Policies strengthening the regulatory framework and enforcing the existing policies will promote market access for all participants and fair competition. Some of the regulations to be strengthened include increased patrols, closed seasons and limiting fishing hours. Infrastructural development at the markets and fish landing sites will enhance the competitiveness of the fish sourced from L. Naivasha. These include acquisition of cold storage facilities, development of road networks and market infrastructure. Promoting value added products will create additional revenue streams, improve livelihoods and increase the competitiveness of the fish from Lake Naivasha. This therefore calls for capacity building of the fish traders for skill acquisition and exploring niche markets. Development of a clear restocking programme and lake cleanup will aid in increasing fish production, translating to increased supply and more revenues.

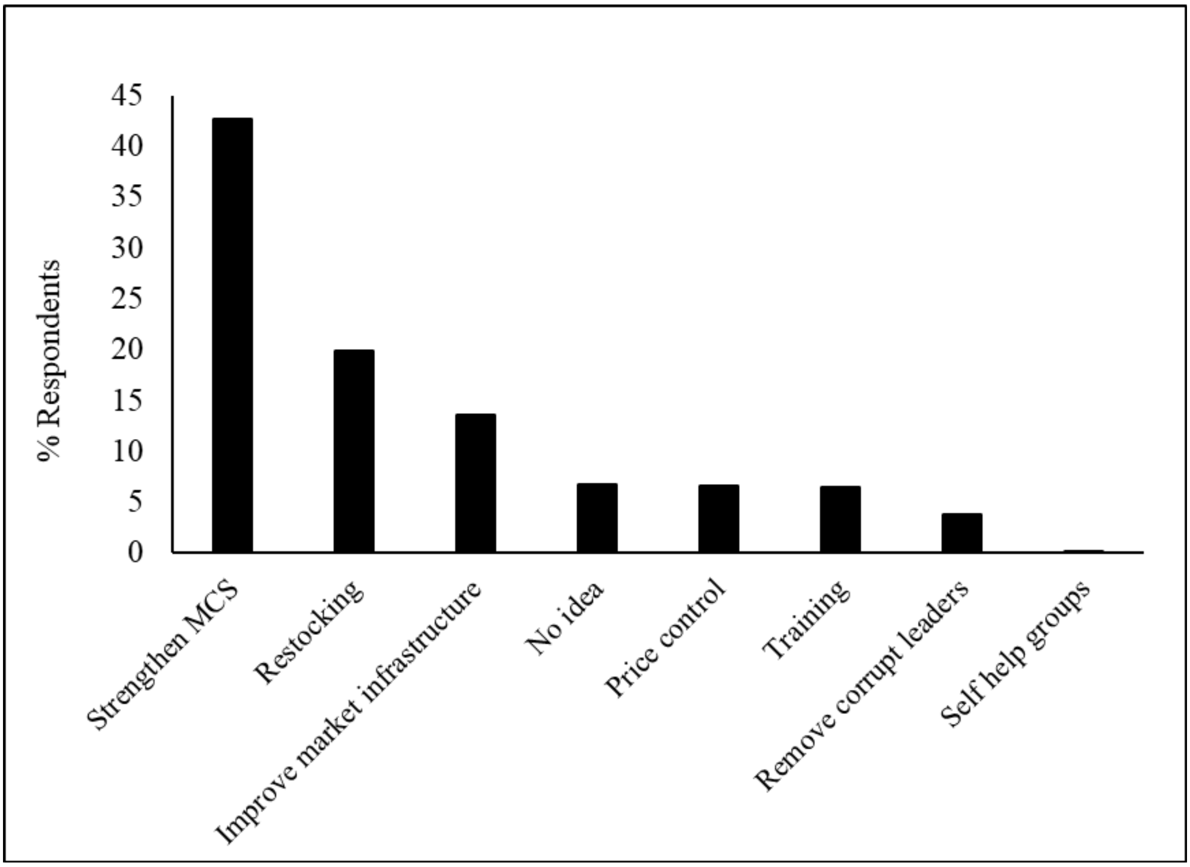

Figure 8. Suggested measures by respondents (%) to improve marketing and management of the fish industry.

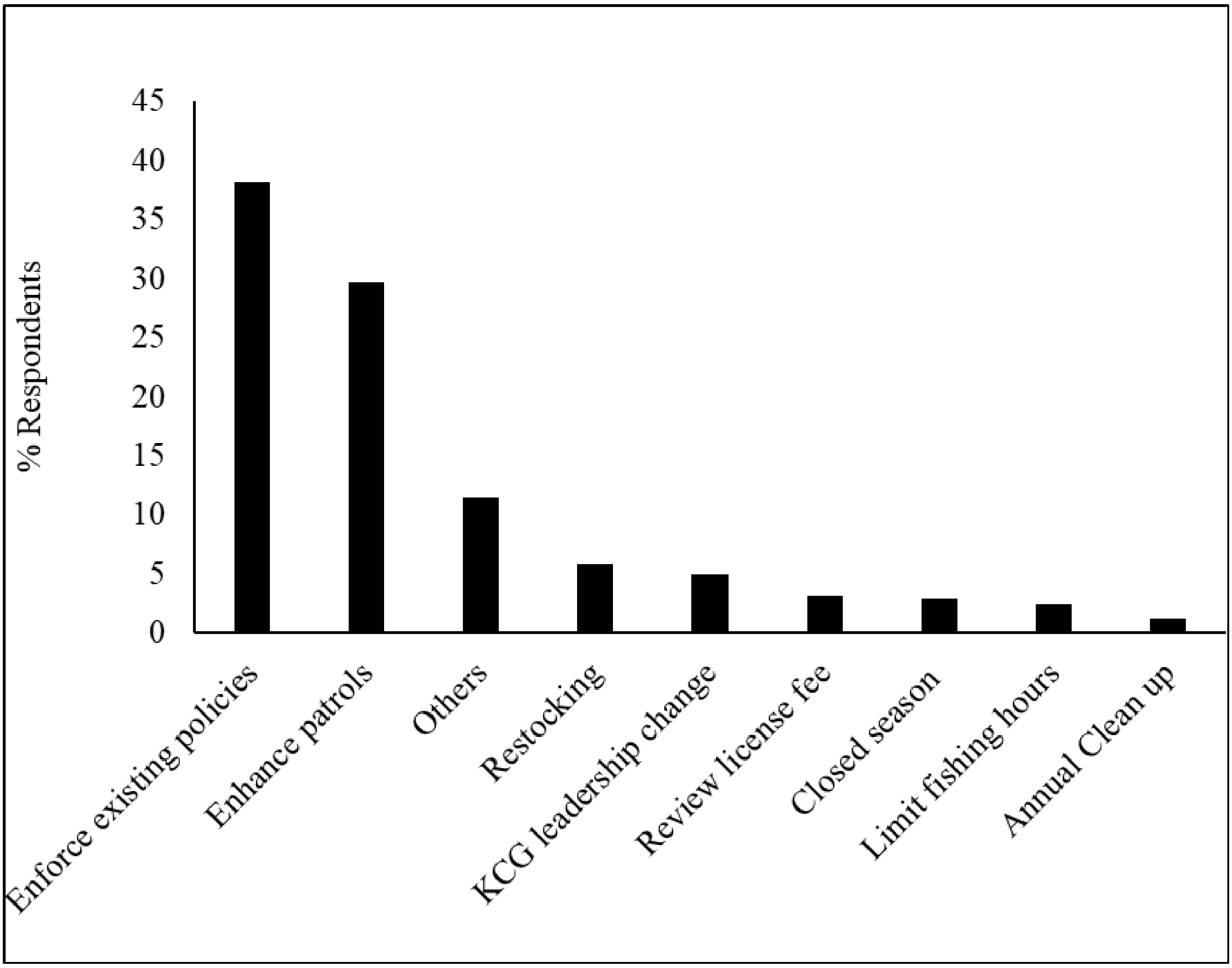

Figure 9. Respondents (%) suggested policies for review and modification.

Conclusions and recommendations

This study concluded that Lake Naivasha fishery is dominated by species like *C. carpio*, *O. niloticus*, and *C. gariepinus,* with retailers being the main players. Fish harvested in Lake Naivasha are sold fresh at the five landing sites, with a larger proportion being transported to market destinations in Nairobi and Nakuru. Major factors influencing market dynamics in the Lake Naivasha fishery are demand/supply and variation in climatic conditions. Challenges faced include infrastructural limitations, low supply of fish as a result of low catch. Some of the strategies that can be employed to improve the fisheries market are investing in infrastructure improvement at the fish *bandas* and the markets, construction of hatcherfes for fingerling production within the county to enable restocking of the lake and training of BMU members and traders and facilitating market access. Implementing and promoting regulations that promote fair competition, transparency, and market access for all market participants is also recommended to improve market performance.

Acknowledgement

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A review on the descriptive approach on disease surveillance and antimicrobial susceptibility profile of bacterial isolates from fish samples in lacustrine caged farms

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Abstract

In Kenya, cage farming has expanded along the shores of Lake Victoria, primarily focusing on the monoculture of tilapia (*Oreochromis niloticus*). Despite the global growth of aquaculture, infectious diseases, particularly bacterial infections are a significant source of economic losses in this sector, especially for cultured tropical freshwater species. There is limited information regarding bacterial communities, prevalence, and patterns of antimicrobial resistance (AMR) in bacteria isolates from caged tilapia on the Kenyan side. This study aimed to give a descriptive and quantitative approach on an investigation of the bacterial communities in caged fish in Lake Victoria and their antibiotic susceptibility. The approach uses examples of study sites of the five riparian counties along Lake Victoria - Migori, Homa Bay, Kisumu, Siaya, and Busia. Currently, there are over 5,635 cages in these counties, with dimensions varying from 8 m² to circular cages of 20 m in diameter. A total of 100 fish samples were collected across the counties as follows: Busia (30), Homa Bay(20), Kisumu (20), Migori (10), and Siaya (20). In the approach, the fish samples underwent clinical examination for disease signs, while parasitological assays were performed on gill biopsies and skin swabs. A bacteriological assay was conducted using aseptically taken kidney swabs, and internal organs were inspected for infectious lesions. Molecular identification of the isolates was conducted at the International Livestock Research Institute (ILRI) in Nairobi, Kenya, using Matrix-Assisted Laser Desorption Ionization–Time of Flight (MALDI-TOF) mass spectrometry (MS). Antimicrobial susceptibility testing (AST) followed standard disk diffusion method as outlined by the Clinical and Laboratory Standards Institute (CLSI). Statistical analysis was conducted to achieve the aim of the objective.

Keywords: cage farming, Lake Victoria, Kenya, infectious diseases, antimicrobial resistance, antimicrobial susceptibility

Introduction

Aquaculture has the potential to significantly contribute to food security, especially as capture fisheries have stagnated over recent decades (Obirikorang *et al.,* 2024). The consumption of fish remains to be essential in the human diet globally and it is a source of important nutrients that are necessary for good health (Wang *et al.,* 2022). Forecasts suggest that the future growth of fish food production will largely stem from aquaculture. For instance, according to FAO (2020), aquaculture production is expected to increase from 60 million metric tonnes in 2010 to 100 million metric tonnes by 2030, and further increase to 140 million metric tonnes by 2050 (Aura *et al.,* 2024).

Food security is recognized as a major global challenge. Despite progress in ensuring safe and nutritious food for all and addressing malnutrition, FAO (2024) estimated that 713 to 757 million people (8.9-9.4% of the global population) faced undernourishment in 2023. According to FAO (2023), as we confront escalating global challenges such as food shortages, limited access to food, and rising food costs - exacerbated by the climate crisis, biodiversity loss, economic slowdowns, worsening poverty, and other overlapping issues - put us at a critical stage. With global populations projected to increase to over 9.7 billion by 2050, seafood in general and fish in particular will continue to play a vital role in providing nutrition and food security globally, especially in developing countries (Obirikorang *et al.,* 2024).

In Africa, fisheries and aquaculture support around 6 million people, a number that continues to rise. In Sub-Saharan countries like Kenya, aquaculture relies mainly on extensive and semi-intensive practices, which hinder production and do not meet the demands of a growing population (Aura *et al.,* 2024). In Kenya, freshwater fish accounts for close to 95% of reported aquaculture production, of which 90% are from Lake Victoria (Orinda *et al.,* 2021). Lake Victoria is revealed to produce more fish than all five Laurentian Great Lakes combined, triple the production of Lake Tanganyika, and more than quadruple the harvest of Lake Malawi (Nyamweya *et al.,* 2023). Tilapia represents about 75% of the total fish produced from aquaculture, followed by African catfish (18%), common carp (6%), and trout (<1%) (Opiyo *et al.,* 2018).

Cage farming has sporadically expanded throughout the shores of Lake Victoria, primarily involving the monoculture of Nile tilapia, *Oreochromis niloticus*, and it has been considered as a game-changer (Obiero *et al.,* 2022). Currently, cage farming is being practiced in five riparian counties including Migori, Siaya, Homabay, Busia and Kisumu, with Siaya County leading with the highest number of cages (Opiyo *et al.,* 2018). The stocking density in the cages ranges between 60 and 250 fish m^{-3}, with cage sizes ranging from 8 to 125 m^3. *Oreochromis niloticus* is the only fish cultured in the lake, with a production of 12 million kg of fish every cycle annually (Opiyo *et al.,* 2018).

Despite the global expansion of aquaculture, diseases significantly contribute to economic losses in the aquaculture industry, with bacterial diseases being the most common and primary cause of mass mortality in fish, particularly affecting cultured tropical freshwater species (Siamujompa *et al.,* 2023). Worsenning the situation, antimicrobial resistance (AMR) in cultured fish has emerged as a major challenge in aquaculture (Preena *et al.,* 2020). AMR is known to arise from mutations or the spread of antibiotic resistance genes (ARGs) and mobile genetic elements (MGEs), largely due to the widespread use of antibiotics (Wang *et al.,* 2022). The AMR is an unavoidable evolutionary phenomenon where by microorganisms including bacteria, viruses, fungi and parasites have the ability to thrive and grow in the midst of drugs designed to kill them, mainly as a result of genetic mutations (Salam *et al.,* 2023). However, long-term overuse of antibiotics in aquaculture has led to acceleration and acquisition of drug resistance (Wang *et al.,* 2022). This AMR can transfer to important strains in nature, impacting the ecosystem (Preena *et al.,* 2020).

Many cultured fish, including ornamental types, carry diverse pathogens with multiple antibiotic resistance (Preena *et al.,* 2020). Studies have also shown that there is a continuous increase in resistance of bacteria to antibiotics due to their widespread use and misuse in fish farming in the treatment of specific and non-specific infections and as growth promoters, resulting in emergence of resistant bacterial strains (Gousia *et al.,* 2011). This makes farmed animals including fish, which are reared majorly for human consumption to become reservoirs of antibiotic resistant bacterial strains. Interestingly, in human beings, AMR has been listed as number one global threat and a significant concern for public health as by the global health security (Velazquez-Meza *et al.,* 2022). Although bacteria intrinsically develop resistance against particular antimicrobials, the significant key factor in the selection of resistant bacteria is probably the use of antibiotic-type and antimicrobial agents for the treatment of diseases and infections in human and animals (Onjong *et al.,* 2021).

According to Onjong *et al.* (2021), AMR is greatly associated with antimicrobials being incorporated into commercial livestock, poultry, and aquaculture production at sub-therapeutic doses to promote growth, improving the feeding efficiency, metaphylaxis and prophylaxis. However, this is immensely unregulated in developing countries. Consequently, due to unregulated use of antibiotics, human beings are indirectly exposed to AMR bacteria through the food chain. Antibiotic resistance determinants found in food and water can be transferred to bacteria of human clinical significance (Onjong *et al.,* 2021).

Numerous studies have been conducted on cage farming in Lake Victoria, Kenya. For instance, Aura *et al*. (2018) reviewed the integration of mapping and socio-economic indicators of fish cage culture in the lake. Njiru *et al.* (2019) reviewed the establishment of cages in the lake and the need for coming up with a decision-support tool for efficient management of the lake. Mwainge *et al.* (2021) conducted a study in determining the fish disease and parasite occurrence in cage culture system. Mboya and Ouko (2023) reviewed the economic aspects of fish cage farming in the lake and Mawundu *et al.* (2023) conducted a study on the effect of stocking density on growth performance, and survival of Nile tilapia (*O. niloticus*) in cage culture system in the lake. Aura *et al.* (2024) did a case study to evaluate the sustainability features of a community-based cage aquaculture that included socio-economic, physical, chemical, biological, production and risks variables that were aimed at identifying and proposing potential mitigation measures for the challenges the cage culture industry may experience. However, there is paucity of information on the bacterial community, prevalence, approach and pattern of AMR- bacterial isolates from caged tilapia (*O. niloticus)* on the Kenyan side of the Lake Victoria. Therefore, the present study targeted to give a detailed or coherent discussion on the approach that is required in investigating the level of bacterial community in caged fish in Lake Victoria and their antibiotic susceptibility. The information from this study is of significance in addressing proper use of antibiotic-type and antimicrobial agents in cage farming in an aquatic environment.

Discussion

The methodology followed in this study is explained in the schematic diagram indicating the flow of processes from sample collection in the field, to the final processes in the laboratory.

Study identification

The review of the approach was based on the five riparian counties along Lake Victoria, Kenya i.e., Migori, Homa Bay, Kisumu, Siaya and Busia counties where cage farming is being practiced (Obiero *et al.,* 2022). Lake Victoria is ranked to be the second largest freshwater lake globally and Africa's largest by surface area and it is being shared by Kenya (6%), Uganda (43%), and Tanzania (51%) (Nyamweya *et al.,* 2023). Currently, the lake is revealed to hold a little over 5,635 cages in the five riparian counties of the Kenyan side with dimensions ranging from 8 m^2 to circular cages of 20 m diameter (Mwainge *et al.,* 2021).

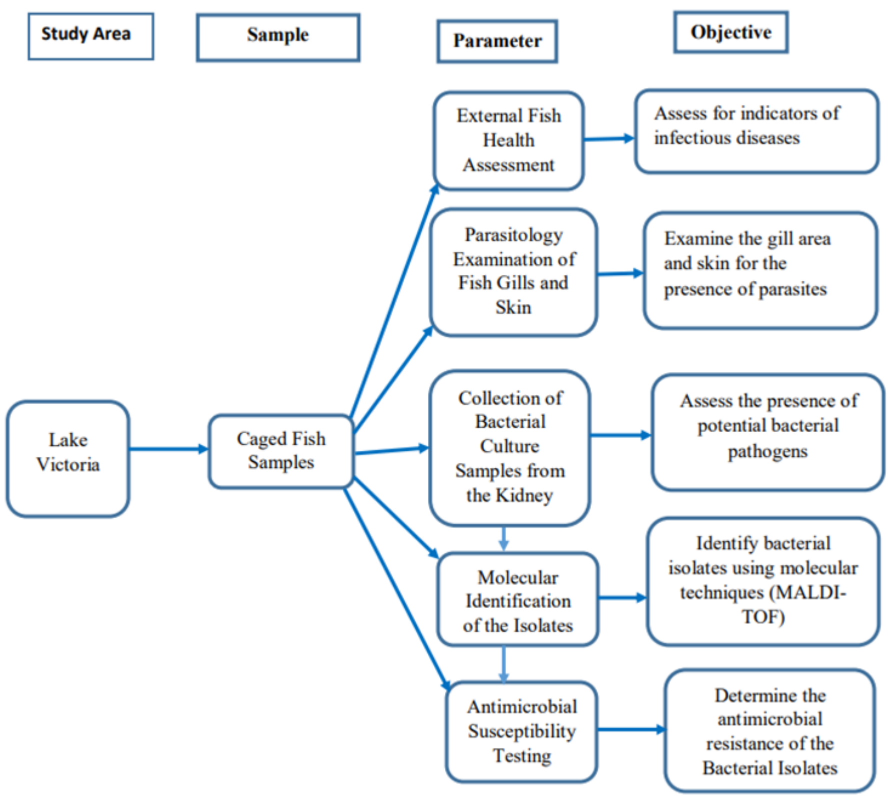

Figure 1. A schematic descriptive approach of the entire process showing the various processes from the sample collection to final laboratory analyses.

Sample collection and sizing

A total of five healthy fish samples, each weighing approximately 200 g or more, were randomly collected from selected cages using a sweep net. The cages from which the samples were taken were also chosen randomly, with consideration given to the distance between the selected cages to ensure diversity. In total, 100 fish samples were collected for analysis from five riparian counties. The distribution of samples included 30 from Busia, 20 from Homa Bay, 20 from Kisumu, 10 from Migori, and 20 from Siaya. Additionally, water samples for metagenomic analysis were collected from the same cages where the fish samples were obtained (Nogueira and Botelho, 2021).

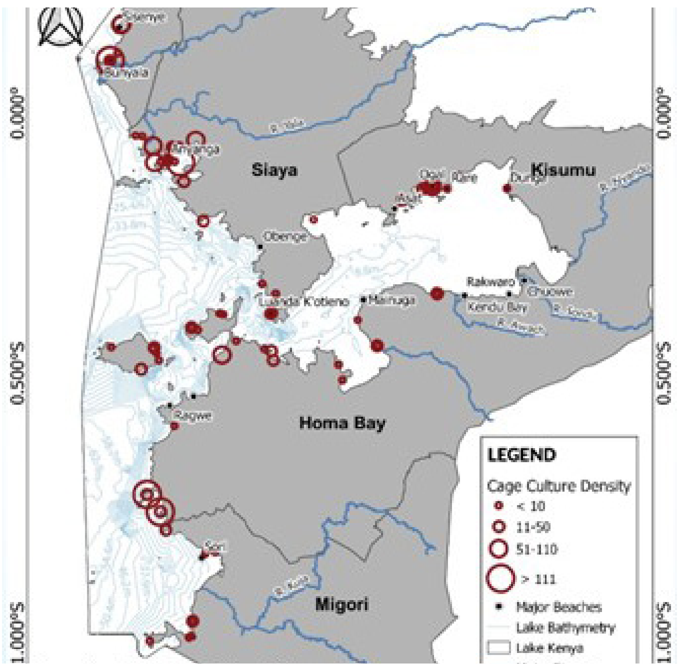

Figure 2. A map illustrating the five riparian counties around Lake Victoria in Kenya where cage farming is practiced and their respective density (Source: KMFRI-ABDP Unpublished Report, 2022).

External fish health assessment

The collected fish samples were first examined clinically for signs of infectious diseases (Mwainge *et al.,* 2021). This assessment involved checking for lesions, ulcerations, deformities such as eye opacity, and skin discolorations on the external parts of the fish. In case of any observations, they were recorded.

Parasitology examination of fish gills and skin

Precise fish gill samples were taken using dissecting scissors and placed on a microscope slide to check for the presence of parasites in the gill area. Two to three drops of distilled water were added to the gill samples to keep the contents fresh and improve visibility during microscopy. Additionally, skin swabs were obtained using coverslips, which were positioned parallel to the gill samples. Both samples were then observed under a compound microscope, and any observable parasites were recorded, noting their number and species (Mwainge *et al.,* 2021).

Bacterial culture sample collection

A bacteriological assay was performed by taking kidney swabs aseptically (Jia *et al.,* 2023). The fish samples were dissected on the dorsal side to expose the internal organs. They were then examined for internal lesions except the kidney to avoid contamination of the site for possible cultures. The swim bladder membrane was carefully dissected to access the kidney, located along the backbone. A sterile hot wire loop was used to puncture the kidney. To avoid contamination, special care was taken to prevent the wire loop from contacting any part of the fish or external objects other than the internal part of the kidney. The swabs were then streaked aseptically onto sterile tryptose agar plates. The inoculated plates were sealed with parafilm and transported to the KMFRI microbiology laboratory. In the laboratory, the plates were incubated at 30°C for 24 to 48 hours, after which bacterial growth was observed. A negative control, consisting of a medium without an inoculum, was also incubated to confirm the sterility of the medium. Only bacterial growth along the streaking pattern was considered. The cultures of interest were sealed with parafilm and preserved in the refrigerator at 2°C as a backup until the process was completed, after which they were discarded aseptically.

Broth culture and glycerol stocks preparation

Colonies of interest were picked from the culture medium and inoculated into sterile broth in sterile test tubes using sterile toothpicks, held with flamed forceps to maintain aseptic conditions. The inoculated broth was then incubated at 30°C for 24 to 48 hours to allow for sufficient growth, which was determined by the turbidity intensity. A negative control, consisting of broth containing only a sterile toothpick, was also incubated to ensure the sterility of the broth. To prepare glycerol stocks, 600 µl of 50% glycerol was pipetted into sterile cryovials, followed by an equal amount of broth culture, and the mixture was homogenized. The vials were labeled according to the various bacterial isolates, with one as a backup. The stock solutions were then preserved in a freezer at -35°C for further analysis.

Molecular identification of the isolates

Molecular identification was performed at the International Livestock Research Institute (ILRI) in Nairobi, Kenya, using Matrix-Assisted Laser Desorption Ionization–Time of Flight (MALDI-TOF) mass spectrometry (MS) (Jia *et al.,* 2023). Spectra acquired from the test isolate were compared with spectra in the reference library and an identification match score was provided based on the similarity to reference library entries. Identification match scores for MALDI-TOF were categorized based on the manufacturer’s guidelines

Antimicrobial susceptibility testing (AST)

Antimicrobial susceptibility testing (AST) against various antibiotics was conducted using the disk diffusion assay in accordance with the Clinical and Laboratory Standards Institute (CLSI) standard methodology for bacterial isolates from the fish samples (Siamujompa *et al.,* 2023).

Data processing

The data analysis for this study was conducted using a combination of statistical methods to assess the bacterial communities and their antimicrobial susceptibility profiles in caged tilapia from Lake Victoria. The analysis aimed to identify patterns of parasite and bacterial prevalence, diversity, and bacterial resistance, providing a comprehensive overview of the health status of the fish populations. Statistical analyses were performed using both Excel and R v.4.3.1 (R Core Team, 2023). Descriptive statistics, including means, standard deviations, and frequencies, were calculated to summarize the data collected from the fish samples.

Prevalence and intensities of infection

This section focused on examining the prevalence and intensity of parasites and the prevalence of bacterial infections affecting caged tilapia (*O. niloticus*) in Lake Victoria.

Prevalence and intensity of parasites

- **Prevalence**: The prevalence of parasitic infections was determined as the proportion of infected fish relative to the total number of fish examined. The formula used was:

  Prevalence =
  (Total number of fish examined ÷ Number of infected fish) ×100.

- **Intensity assessment**: The intensity of infection was calculated as the average number of parasites per infected fish. This provided insight into the severity of parasitic infestations.

Prevalence of bacteria

- **Bacterial prevalence**: The prevalence of each bacterial species was calculated as a percentage of the total number of samples tested. This was done by dividing the number of positive samples for each species by the total number of samples

  collected and multiplying by 100.

Antimicrobial susceptibility testing (AST): The results from the disk diffusion method were interpreted according to the Clinical and Laboratory Standards Institute (CLSI) guidelines. The diameters of inhibition zones were measured in millimeters, and bacteria were classified as susceptible, intermediate, or resistant based on these measurements.

Diversity analyses

The diversity of both bacterial and parasite communities was assessed using the Shannon-Wiener index (H') and Simpson's index (D). These indices provide insights into both species richness and evenness within the samples:

- **Shannon-Wiener Index (H')**: This was calculated using the formula:

  $$H'=-\Sigma(pi \cdot \ln(pi))H'=-\Sigma(pi \cdot \ln(pi))$$

  where *pi* is the proportion of each species of bacteria or parasite in relation to the total number of species.

- **Simpson's Index (D)**: This index was computed using the formula:

  $D=\Sigma(pi2)D=\Sigma(pi2)$.

The results from these indices help in understanding the ecological balance within the caged fish populations and can indicate potential impacts on fish health.

Multivariate analyses

A principal coordinate analysis (PCA) was employed to visualize differences in bacterial and parasite communities among samples from different counties. This multivariate approach allows for an assessment of how geographical variations may influence the parasite and microbial diversity and antibiotic resistance patterns.

Conclusions and recommendations

This study provides insights on the approach required during the investigation of the parasitic and bacterial communities in caged tilapia fish (*O. niloticus*) and their antibiotic susceptibility in a lacustrine environment. This is because there is limited information about the bacterial communities and the prevalence and patterns of antibiotic-resistant bacteria (AMR) isolated from caged tilapia in the lake. Despite the global growth of aquaculture, infectious diseases, especially bacterial infections pose a significant economic challenge in this sector, particularly for cultured tropical freshwater species. Antimicrobial resistance in cultured fish presents a major obstacle, with antibiotic use largely unregulated in developing countries. The approach of this study will provide crucial insights into the responsible use of antibiotics and antimicrobial agents in cage farming practices in the region, in accordance with legal and environmental standards.

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