INFLUENCE OF CAGE FISH FARMING ON WATER QUALITY: THE CASE OF TENDE BAY, LAKE VICTORIA, UGANDA

MSc THESIS IN TRANSFORMATIVE COMMUNITY DEVELOPMENT

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MZUZU UNIVERSITY

DECEMBER, 2025

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BSc in Environmental Management (University of Livingstonia)

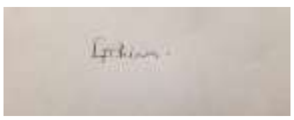
A THESIS SUBMITTED TO THE FACULTY OF ENVIRONMENTAL SCIENCES, DEPARTMENT OF AGRI-SCIENCES IN FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF SCIENCE DEGREE IN TRANSFORMATIVE COMMUNITY DEVELOPMENT

MZUZU UNIVERSITY

DECEMBER, 2025

DECLARATION

I hereby declare that this thesis titled, *"Influence of cage fish farming on water quality: The case of Tende Bay, Lake Victoria, Uganda"* has been written by myself and is a record of my research work. All citations, references, and borrowed ideas have been duly acknowledged. It is being submitted in fulfillment of the requirements for the award of the degree of Master of Science (MSc) in Transformative Community Development at Mzuzu University. None of the present work has been submitted previously for any degree or examination in any other university.



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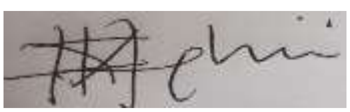

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DEDICATION

I dedicate this work to my parents, Mr. Oscar and Mrs. Anna Chirwa, my pillar of strength and unwavering support system.

ACKNOWLEDGEMENTS

My sincerest thanks go to God Almighty for the gift of life and all the amazing blessings in my life, may His name be praised always. I am immensely grateful to COTRA for blessing me with a life-changing scholarship that has allowed me to pursue my research at Makerere University. This opportunity has been a true gift from above, and I am forever thankful for the support.

I would also like to express my profound gratitude to my supervisors Associate Prof. Mtafu Manda, Dr. Ronald Semyalo, Dr. Frank Mnthambala, and Dr. Robinson Odong for all the help, advice, availability and support throughout this study. Their cajoling gave me impetus during tricky period of writing this thesis. Thank you also to Luke Odur, the Lab Technician at Makerere University, for his invaluable help with data collection and lab work. I would like to express my heartfelt gratitude to Dr. P. Akoll and Bob Jere, the dedicated coordinators at COTRA, for their unwavering support throughout my studies. I am fully aware that the path was not without challenges, but your tireless efforts ensured that everything went smoothly. Your commitment and exceptional guidance have played a vital role in my academic journey, and I am truly grateful for your invaluable contributions.

To my lovely family you people are awesome and I am thankful for you all.

ACRONYM AND ABBREVIATIONS

ANOVA:	Analysis of Variance
ASC:	Aquaculture Stewardship Council
BAP:	Best Aquaculture Practice
BOD:	Biological Oxygen Demand
COD:	Chemical Oxygen Demand
CONAMA:	National Environmental Council
FAO:	Food and Agriculture Organization of the United Nations
GPS:	Global Positioning System
HVLD:	High Volume in low-density
LVHD:	Low Volume in High Density
MAAIF:	Ministry of Agriculture, Animal, Industry and Fisheries
MGDS:	Malawi's Growth and Development Strategy
NDP:	National Development Plan
RAS:	Recirculating Aquaculture System
SDG:	Sustainable Development Goal
SON:	Source of Nile
SRP:	Soluble reactive Phosphorus
USD:	United States Dollar
WHO:	World Health Organization

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ABSTRACT

The expansion of cage fish farming in Lake Victoria has raised concerns about its potential impacts on water quality and aquatic ecosystems. This study was conducted in Tende Bay from August to October 2023. Its objectives were to examine the relationship between cage fish farming and physicochemical parameters and to assess its effects on zooplankton diversity. A comparative study design was used, sampling four sites: two adjacent to cages (Sites 1 and 2, ~10 m from cages), one at 50 m distance, and an offshore control site 100 m from the shoreline. Water quality parameters measured included temperature, pH, dissolved oxygen (DO), and nutrient concentrations including nitrogen (N), phosphorus (P), and ammonia (NH_3) as well as chlorophyll levels. Statistical analysis (ANOVA, $p < 0.05$) indicated a significant increase in nutrient concentrations near the cages, with ammonia ranging from 0.03 to 0.57 mg/L and total phosphorus from 0.12 to 0.30 mg/L. These elevated nutrients, attributed to fish feces and feed waste, did not correspond with significant changes in chlorophyll levels across sites. Zooplankton diversity and composition differed significantly between cage sites and the offshore control (Shannon's index, $p = 0.03$), with rotifers showing higher abundance compared to Cladocera near cages. Despite nutrient increases, temperature (25.52–25.63°C), pH (7.84–9.15), and DO (3.62–4.81 mg/L) remained within acceptable ranges for aquatic life. Elevated NH_3 levels near cages (up to 0.57 mg/L) underline the need for continuous monitoring. While no consistent environmental degradation directly linked to cage farming was detected, the study recommends implementing regular water quality assessments and nutrient management strategies to ensure sustainable aquaculture practices in Lake Victoria."

Key words: *cage fish farming, nutrient concentrations, physicochemical parameters, zooplankton diversity, water quality*

CHAPTER ONE: INTRODUCTION

1.1 Introduction

This chapter serves as a critical foundation for understanding the influence of cage fish farming on water quality within the context of Uganda's Lake Victoria. As aquaculture continues to evolve, the historical development and various methods of fish farming, with a specific emphasis on cage culture, are explored to provide a comprehensive backdrop for this investigation. The discussion highlights the pressing environmental concerns associated with these practices, particularly their impact on water quality, which is vital for sustaining aquatic life.

1.2 Background of the study

1.2.1 Historical development of aquaculture

Globally, from 1950 to 2018, the combined production of fisheries and aquaculture increased from 19 million tons to approximately 179 million tons with an average annual growth rate of 3.3 percent (FAO, 2020). The total value of fisheries and aquaculture production for aquatic animals in 2020 was estimated at USD 406 billion, with aquaculture contributing USD 265 billion to the overall value. The demand for fish and seafood has been steadily increasing due to factors such as population growth, rising incomes, and shifting dietary preferences (Naylor, 2021). According to the State of World Fisheries and Aquaculture report by the FAO (2020), the contribution of regional fisheries and aquaculture production to global capture fisheries and aquaculture production varied widely across regions. Asia and Oceania were the major contributors to global fisheries and aquaculture production, with Asia accounting for over 85 percent of global aquaculture production. In contrast, Africa and Europe accounted for only a small share of global fisheries and aquaculture production.

Different types of fish are used in aquaculture, including tilapia, catfish, salmon, trout, carp, and bass, as well as shellfish like shrimp, oysters, and mussels (Froehlich, 2022). The choice of fish species depends on various factors such as market demand, climate, water quality, and availability of seed (Froehlich, 2022). According to the Food and Agriculture Organisation (FAO), fish contributes around 17% of the global population's intake of animal protein, making it an essential component of the human diet (FAO, 2020). Furthermore, fish consumption is projected to grow by 12% globally by 2030 (FAO, 2010). In addition, Aquaculture plays a crucial role in meeting the increasing demand for seafood. Aquaculture has experienced substantial growth to become one of the fastest-growing food production sectors globally (Muir, 2007). In 2018, aquaculture accounted for nearly 53% of global fish production, surpassing wild-caught fish for the first time (FAO, 2020).

1.2.2 Aquaculture methods and practices

According to (e Gouvello, 2017), various aquaculture techniques are employed around the globe to breed a wide range of organisms in three different habitats namely: freshwater, brackish water and marine environments. In recent years, the growth of global fish supplies has slowed significantly. According to a FAO report, *The State of World Fisheries and Aquaculture 2022*, the average annual growth rate of aquaculture production declined from 5.1% in the 2001-2010 period to 4.0% in the 2011-2020 period (FAO, 2022). Despite this slowdown, aquaculture remains the only sector experiencing consistent growth, contributing more than 50% of the total fish supply for human consumption in 2020. As a result, offshore areas beyond the immediate near shore waters are becoming increasingly attractive for aquaculture (FAO, 2020).

Among the various aquaculture systems available, cages are the most versatile as they can be deployed in various environments such as inland waters, estuaries, coastal regions, and the open sea (Norouzi, 2021). Technological advancements have brought about improvements and diversification in cage designs. Caging provides controlled confinement, while allowing water to flow through the cages freely, providing a natural environment for the organisms (Morris, 2013). Another method is pen culture, where aquatic organisms are confined within defined areas created by natural barriers or artificial enclosures. Pens offer partial confinement and water exchange with the surrounding environment (Munawar, 2021). Additionally, other methods include pond culture, where organisms are reared in specially designed ponds, and Recirculating Aquaculture Systems (RAS), which use closed systems to recycle and treat water for optimal sustainability (Cheung, 2019). Each method has its advantages and can be adapted to specific species or environmental conditions to ensure the sustainable production of aquatic organisms. According (FAO, 2022), pond culture accounts for approximately 60% of global freshwater aquaculture production, cage culture 25%, and pen culture 5%, with the remainder from other systems.

1.2.3 Cage culture

Cage systems can be classified into four basic types: fixed, floating, submersible, and submerged (Beveridge, 2004). Over the past two decades, there have been significant developments in cage technology, particularly in the design of coastal and offshore marine systems (Fitzsimmons, 2013). These advancements have opened new possibilities for expanding aquaculture production in marine environments.

Growing fish in cages is practiced in many parts of the world but has in the last 20 years become a popular fish farming practice in Africa, specifically in Ghana, Kenya, Malawi, Uganda, Zambia and Zimbabwe (Leonard, 2007). In comparison to traditional pond culture systems, the advantage of cage fish culture technology is the possibility of growing a large number of fish in a relatively small area of water (Javanbakht, 2022). For example, in 8-12 m^3 cages, one can raise one ton of fish in 8 months. In addition, cages can be easily fabricated from locally available materials such as netting mesh, steel bars or bamboo stem frames, plastic floaters, stone sinkers and ropes (Alam, 2021). Culturing fish in cages affords greater production rates compared to pond systems (Ndawula, 2013).

In the East African region, cage fish farming has not been widely practiced despite a large market for fish in the region and known potential of the practice (Blow, 2007). Cage fish farming is currently practiced by few commercial fish farmers and is a direct response to declining fish harvests from wild fish stocks and increasing market demand from local, regional, and international markets (Beveridge, 2004).

1.2.4 Cage fish farming in Uganda

According to the Uganda Ministry of Agriculture, Animal Industry and Fisheries (MAAIF, 2014), the aquaculture sector in Uganda is one of the fastest growing sectors. Aquaculture in Uganda is carried out in diverse environments, including naturally occurring water bodies like lakes, rivers, and swamps, as well as in constructed water bodies such as ponds and tanks (Ssentongo, 2015). Nile tilapia is a prominent species cultivated within Uganda's aquaculture industry (FAO, 2010). The advent of cage farming on Lake Victoria and the entry of major international fish farmers have been drivers of the fast growth (Polidoro, 2011). Uganda is promoting cage fish farming to improve household incomes and food security (MAAIF, 2014). Production figures of a fish farm in northern Lake Victoria indicate high potential for cage fish culture with an increase in yield from 290 tons in 2011 to 402 tons in 2012 and 506 tons in 2013, corresponding to 147, 205 and 269 cages, each of approximately 15.625m^3 volumes, respectively.

1.2.5 Environmental concerns of fish farming in cages

Aquaculture produces waste that can negatively impact the environment (Bhatnagar, 2013). In intensive aquaculture systems, where feed is provided, a significant amount of organic waste accumulates, consisting of both particulate matter (mainly uneaten food and fish feces) and soluble substances (excreta). This waste leads to an increase in biochemical oxygen demand (BOD) and higher concentrations of dissolved nitrates and phosphates in the water. The waste generated from fish farming significantly impacts aquatic ecosystems by increasing biochemical oxygen demand (BOD) and elevating concentrations of dissolved nitrates and phosphates in the water (Campbell, 2019).

Approximately 50% of the nitrogen and carbon from the feed is excreted through the gills of fish in dissolved forms, contributing to nutrient pollution and promoting microbial growth, which further depletes oxygen levels (Komakech, 2015). Additionally, more than 50% of the phosphorus is released as particulate matter in faecal waste, along with uneaten feed, which settles on the seabed (Njiru, 2018). This particulate matter undergoes decomposition, releasing nutrients back into the water column and exacerbating the problem of eutrophication, ultimately leading to detrimental effects on water quality and aquatic life (Komakech, 2015).

The environmental effects of aquaculture are significantly influenced by feed quality and feeding strategies. Nutrients that are not absorbed by fish or shrimp are expelled into the environment, where they can accumulate and potentially cause ecological problems. Research indicates that nutrient enrichment from fish excreta and uneaten feed can lead to eutrophication, which depletes oxygen levels and adversely affects aquatic life (Dauda, 2019). Whether a nutrient acts as a pollutant in an aquatic system depends on its role as a limiting nutrient, its concentration, and the ecosystem’s carrying capacity (Njiru, 2008).

In freshwater systems, phosphorus is usually the limiting nutrient, meaning its addition can significantly influence primary production, such as algal growth (Rabalais, 2002). Conversely, in marine environments, nitrogen typically serves as the limiting nutrient, and its introduction will similarly affect production levels (Jansen, 2016). Excess nutrients are released into the environment in two forms: dissolved nutrients and particulate matter. Similarly, research from Africa, including Egypt and Tunisia, reveals that cage farming can degrade water quality through elevated levels of organic matter, turbidity, and pathogens. Factors contributing to these environmental issues include high stocking densities, poor feed quality, insufficient water exchange rates, and inadequate management practices (Glibert, 2017). The scale of the problem is significant, with cumulative effects leading to long-term declines in fish populations and biodiversity. Key threats include eutrophication, outbreaks of fish diseases, disruption of local fisheries, and habitat loss.

In Uganda, the expansion of cage fish farming is raising concerns, particularly in vital water bodies like Lake Victoria, where increased nutrient loading correlates with the rise of aquaculture. Reports suggest that this nutrient enrichment is contributing to water quality deterioration, leading to harmful algal blooms and reduced oxygen levels (Njiru, 2018). Additionally, the introduction of non-native fish species raises concerns about impacts on local fish populations and biodiversity (Kolding, 2014). Thus, Uganda must be vigilant regarding the sustainability of its cage fish farming practices.

Uganda relies on fisheries for protein, making any adverse effects on fish populations a significant threat to food security and economic stability (Munguti, 2024). Protecting the ecological integrity of Uganda’s lakes is crucial for maintaining biodiversity and ecosystem services that benefit human populations. Additionally, it is important to address the regulatory challenges that arise with the expansion of the industry (FAO, 2022). By learning from both regional and global experiences, Uganda can proactively ensure that its aquaculture practices are sustainable and environmentally responsible. This approach will help safeguard its natural resources and protect the livelihoods of its people (Weeratunge, 2013).

1.3 Problem Statement

The rapid expansion of cage fish farming in Uganda, particularly in Lake Victoria, presents a complex array of environmental challenges that threaten both aquatic ecosystems and the livelihoods of local communities (Nyakeya, 2023). While cage fish farming has the potential to significantly enhance food production and stimulate economic growth, it simultaneously introduces serious ecological risks. The practice leads to nutrient enrichment from fish excreta and uneaten feed, which can trigger eutrophication, a process that depletes oxygen levels in the water and promotes harmful algal blooms. These blooms not only degrade water quality but also pose severe risks to aquatic life, disrupting the delicate balance of the ecosystem (Ejiohuo, 2024).

As water quality deteriorates, the health of fish populations and other aquatic organisms is compromised, which directly impacts local fisheries. Fishers who depend on these resources for their livelihoods face declining catches, threatening their economic stability and food security. This situation is particularly dire for communities that rely on fish as a primary source of protein, making the implications of poor water quality a pressing public health concern (Masese, 2025).

The cage farming sector's high stocking densities and inadequate management practices create additional layers of complexity for these challenges. These factors exacerbate the negative impacts on water quality, leading to further ecological degradation (Njiru, 2022). The lack of effective regulatory frameworks to govern aquaculture practices in Uganda complicates the situation, as there are insufficient guidelines to mitigate the environmental impacts associated with cage fish farming. This regulatory gap highlights the urgent need for sustainable aquaculture strategies that can balance the economic benefits of fish farming with the imperative to protect natural resources (MAAIF, 2014).

Given these pressing issues, it is essential to investigate the specific influence of cage fish farming on water quality in Uganda. Understanding these dynamics is crucial for developing actionable recommendations that not only safeguard aquatic ecosystems but also support the welfare of local communities (Nyamweya, 2023). This study aims to clarify the environmental implications of cage fish farming, focusing on its effects on water quality and the broader ecological consequences for Lake Victoria, ultimately contributing to the formulation of sustainable practices that can enhance both food security and environmental health.

1.4 Study Objectives

1.4.1 Main Objective

The overall objective of this study was to assess the influence of cage fish farming on water quality of Tende Bay, Lake Victoria.

1.4.2 Specific objectives

a. To determine the relationship between cage fish farming activity and hydro-physicochemical parameters in Tende Bay, Lake Victoria.

b. To estimate the diversity of zooplankton in the designated sampling areas of the lake and assess their association with cage fish farming.

c. To analyse the correlation between nutrient concentrations (nitrogen, phosphorus, and ammonia) and chlorophyll levels in sampling sites.

1.4.3 Research Questions

a. How does the accumulation of fish waste influence the physicochemical parameters of water?

b. What are the dominant zooplankton species in the sampling areas, and how does their composition indicate the lake's ecological health?

c. How do nutrient concentrations in water samples vary between areas with cage culture and control sites?

1.5 Justification

The study is relevant to Uganda's National Development Plan III (NDP III)**,** which emphasizes sustainable agricultural practices, environmental conservation, and food security. By providing baseline data for monitoring water quality and guiding sustainable aquaculture practices, the study will be supporting the development of Uganda's fish farming industry while preventing environmental degradation. The study also supports Malawi's Growth and Development Strategy III (MGDS III) by offering insights that will be guiding the sustainable expansion of aquaculture in Lake Malawi, contributing to food security and natural resource management.

On a broader scale, the study will be contributing to SDG 2 (Zero Hunger)**,** SDG 6 (Clean Water and Sanitation), and SDG 14 (Life below water) by promoting sustainable fish farming and protecting aquatic ecosystems. It will also be supporting Africa Agenda 2063, particularly Aspiration 1 (sustainable development) and Aspiration 7 (environmental sustainability), by ensuring that aquaculture growth is both economically beneficial and ecologically responsible.

These findings will be critical for shaping national, regional, and international policies on biodiversity conservation and sustainable aquaculture practices.

1.6 Conclusion

This chapter has established a critical foundation for examining the influence of cage fish farming on water quality, detailing the historical development and various methods of aquaculture, with a specific focus on cage culture in Uganda. The discussion has highlighted the environmental concerns arising from these practices, particularly their impact on water quality, which is essential for both aquatic life and human health. Through the problem statement and clearly defined study objectives, the research has identified key research questions that will guide this investigation into the complex interrelationship between cage fish farming and water quality. This study is justified not only by the need to address potential environmental degradation but also by the importance of sustainable aquaculture in promoting food security and economic development in Uganda. The insights provided in this chapter will serve as a crucial reference point for the subsequent analyses, aimed at fostering practices that safeguard water quality while enhancing the benefits of cage fish farming.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter presents a thorough examination of the existing literature surrounding cage fish farming and its implications. Structured according to the research objectives outlined in Chapter One, it also provides a comprehensive analysis of various aspects related to this aquaculture method. Through an exploration of cage fish farming techniques, lake water quality, and critical water quality parameters, this review offers valuable insights into the importance of water quality in aquaculture. It also investigates the water quality changes associated with cage farming and evaluates the impact of fish cage farming on the aquatic environment. By synthesizing these elements, this literature review aims to enhance understanding of how cage fish farming practices influence both aquatic environments and local communities, particularly in the context of Lake Victoria.

2.2 Cage fish farming technique

Cage culture, also known as net-pen culture, consists of a net suspended in the water column with a flotation system around its perimeter. Most often the net is hung in a square or rectangular configuration (four sides and a bottom), but some cage systems employ circular nets. The size of a cage can vary considerably depending on the needs of the culturist: a small cage may enclose an area of only a few square meters; larger cages, particularly those intended for use in offshore areas, may enclose 500 m^2. The depth of the cage usually varies from 3 to 15 m. The cage is moored by one or more anchor lines extending out from the perimeter.

Figure 1: Fish cage in Lake Victoria, Tende Bay (Photo by Esther Chirwa, 9 August, 2023)

Cage aquaculture involves growing fish at High Density in Low Volume (LVHD) cages of less or equal to 30 m^3 or Low Density in High Volume (HVLD) cages of more than 30 m^3 suspended and secured in water, while maintaining free exchange between the enclosure and the water body (Leonard, 2007). Cage fish farming offers great potential to increase fish production to meet the deficit in fish supply. It can, however, pose environmental threats and conflicts with other water uses and requires adequate guidance. This requires effective policies, institutions and manpower; proper siting, farm layout, fabrication and installation; good production practices; and environmental monitoring (Wanja, 2020).

Fish farms typically consist of multiple cages that are either moored close together or physically connected to form large arrays. These cages can be rectangular, circular, or cylindrical in shape and generally include components such as a cage frame, cage bag, floaters, feed enclosures or barriers, cage covers, and sinkers. The mesh size of the cage bag is usually around 8 mm for nursery cages and 13 mm for grow-out cages, ensuring that the cages are strong enough to retain the fish securely (Thomas, 2009). Globally, over 90% of farmed salmonids are raised in marine cage systems. However, due to the wide salinity tolerance of salmonids and varying aquaculture practices worldwide, production methods differ significantly by region (Verdegem, 2003). For example, in Scotland, approximately 14% of rainbow trout are farmed in marine cages, while 42% are produced in freshwater cages, with the remainder raised in freshwater ponds and tanks. In Finland, about 85% of farmed rainbow trout come from brackish-water cages, with the rest from freshwater systems. Recently, many countries have shown a trend toward shifting trout production from freshwater environments to marine cage systems (Namin, 2022). These variations highlight the diversity of salmonid aquaculture practices and the importance of adapting cage culture to local environmental conditions.

Low-Volume High-Density (LVHD) cage fish farming began in Uganda in 2006 and has demonstrated significantly higher production rates of 150–300 kg/m^3 compared to the 2–10 kg/m^3 achieved through pond culture, which was introduced over 60 years ago (Thomas, 2009). Cage fish farming is expanding rapidly in Uganda, particularly on Lake Victoria, where the number of cages has grown from fewer than 100 to over 3,000 (MAAIF, 2014). This growth is not limited to Lake Victoria but is also spreading to other water bodies across Uganda and other African lakes.

2.3 Lake water quality

Lake Victoria water plays a crucial role in fish cage culture due to its significance in supporting the growth and production of fish. The quality of water in Lake Victoria directly impacts the success of fish cage culture. Good water quality optimizes fish growth and enhances their overall health (Nyamweya, 2023).

Fish cage culture in Lake Victoria provides essential nutrients, oxygen, and a suitable environment for fish to thrive, benefiting significantly from the natural resources available in the water. The lake is rich in phytoplankton and zooplankton, which serve as natural food sources for fish, while the generally favourable water temperature and pH levels further support fish growth (FAO, 2022).This aligns with findings by (Musinguzi, 2019), who highlighted the rapid expansion of cage aquaculture on African inland waters, including Lake Victoria, and emphasized the importance of adhering to best practices for sustainability. Despite these benefits, maintaining a balance between fish farming and the quality of Lake Victoria's water is critical.

Anamarija and Martinez-Porchas (2012), noted that uncontrolled aquaculture activities could negatively impact water quality, leading to eutrophication and ecosystem imbalances. (Musinguzi, 2019), also reflected on the importance of sustainable aquaculture practices, urging for proper management to mitigate environmental degradation caused by the increasing number of fish cages. By adhering to sustainable practices and monitoring ecological impacts, fish cage farming can continue to benefit from Lake Victoria's natural resources while maintaining the health of its aquatic ecosystem.

Excessive fish farming effluent, such as nutrients and feed, can lead to water pollution and negatively impact the overall water resources. Therefore, sustainable fish cage culture in Lake Victoria requires minimizing the release of effluents and ensuring that potential negative impacts on the natural environment are minimized (Munawar, 2022). Overall, recognizing the importance of Lake Victoria water in cage fish culture is crucial for maximizing fish production while preserving the integrity of the lake's ecosystem (Njiru, 2008). The water quality of Lake Victoria can be assessed through various parameters, including dissolved oxygen (DO), pH, salinity, conductivity, total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), total carbon (TC), biological oxygen demand (BOD), and more. The water quality of Lake Victoria is typically assessed using parameters such as dissolved oxygen (DO), pH, salinity, conductivity, total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), total carbon (TC), and biological oxygen demand (BOD), each with general threshold ranges that indicate the lake's health over time.

Dissolved oxygen levels above 5 mg/L are ideal to support aquatic life, while pH usually ranges between 6.5 and 9.0, suitable for freshwater ecosystems. Salinity remains very low, reflecting its freshwater status, and conductivity generally falls within typical freshwater ranges but can increase with pollution. TSS values are ideally low to maintain clarity, often below 25 mg/L, while nutrient concentrations such as TP and TN are critical indicators of eutrophication risk, with TP levels ideally below 0.02 mg/L and TN below 0.3 mg/L to prevent excessive algal growth. Biological oxygen demand should remain under 3 mg/L to avoid oxygen depletion from organic pollution. Deviations from these thresholds, especially elevated nutrients and BOD or reduced DO, signal deteriorating water quality and ecosystem imbalance, often linked to human activities and pollution pressures on the lake (Worthington, 2009). These parameters help evaluate the overall health and condition of the lake's water (Chidiac, 2023), According to (Mishra, 2008), fish culture activities can have an impact on water bodies, particularly when aquaculture is practiced in ponds or cages located near surface water bodies. In such cases, water is often diverted from streams into the aquaculture facilities for fish production, and the resulting effluent from these facilities is discharged back into lakes, rivers or streams without proper wastewater treatment (Saremi, 2013).

2.4 Water quality parameters

2.4.1 Temperature

Temperature varies with ambient conditions such as solar radiation, presence of vegetation, cloud cover, geographical location, and change in daily diurnal patterns and time of sampling (Dong, 2012). Temperature plays a crucial role in aquatic environments and has a significant impact on fish physiology, metabolism, reproduction, and growth. Fish are poikilotherms, meaning they do not produce their own body heat and rely on the surrounding water temperature. Each fish species has an optimal temperature range within which it thrives, with warm-water fish typically thriving at temperatures between 28-32°C (Souchon, 2012). Fish are also unable to regulate their body temperature but follow the water temperature. Higher or lower temperatures outside the optimal range are stressful or lethal. Fish eggs will only hatch at certain optimal temperature. Increase in temperatures decrease solubility of dissolved oxygen and other gases. Increase in temperature accelerates feeding, movement and respiration (Anon., 2022).

The amount of dissolved oxygen in water is influenced by temperature, and it plays a crucial role in the survival and growth of aquatic organisms. Temperature also affects the metabolic rate of aquatic organisms, including fish. Solar radiation is a primary source of heat for water bodies, and it raises water temperature when sunlight is absorbed. Heat loss occurs through direct exchange with the atmosphere and circulation with the substratum (Pisupati, 2023). Solar radiation is the source of heat for water bodies when sunlight strikes the surface of the water, heat is absorbed into the water raising the water temperature while loss of heat is by direct exchange to the atmosphere and circulation with the substratum. The optimal temperature range for tropical fish survival is generally considered to be between 28 and 32°C (Subagja, 2021). However, different fish species have varying thermal tolerances. An acceptable temperature range for aquaculture purposes is 15°C to 35°C (Mugwanya, 2022).

2.4.2 Dissolved Oxygen

Dissolved oxygen (DO) is a vital water quality parameter in aquaculture as it is essential for supporting life in water. It plays a critical role in the respiration of living organisms, decomposition of organic matter, and chemical oxidation of water and sediments (Verma, 2022). DO enters the water through diffusion, as a result of photosynthesis. Temperature affects the rate of oxygen diffusion into the water, thereby impacting DO levels.

DO concentrations are measured in milligrams per litre (mg/L) or parts per million (ppm) (Burns, 2005). The abundance of planktonic algae significantly influences photosynthesis, which releases oxygen and increases DO levels in aquaculture ponds. On the other hand, respiration by organisms consumes oxygen and reduces DO in the water. The presence of organic matter in water leads to decomposition, which consumes oxygen and results in lower DO levels (Li, 2022).Lack of DO is a common cause of fish mortality in ponds. The optimum DO level for aquaculture should be above 5 mg/L, although catfish and tilapia fish can tolerate DO levels of 3 mg/L and above (Mohsen, 2015). Concentrations of DO below 5 mg/L can lead to reduced feed intake, higher feed conversion ratio (FCR), slow growth rate, stress, and increased susceptibility to diseases, and DO levels below 1 mg/L can be lethal to fish. The World Health Organization (WHO) recommends an acceptable limit for water quality of 4-6 mg/L. Low DO levels can be managed by controlling algae growth or using aeration devices to enhance oxygen transfer into the water (Chislock, 2013).

Maintaining specific water quality parameters is crucial for the well-being of aquatic organisms. Parameters such as dissolved oxygen (DO) levels, temperature, pH, ammonia, nitrate, and nitrite concentrations, and suspended solids should be within appropriate ranges for optimal fish growth and health (Pranta & Rahaman, 2023). Insufficient dissolved oxygen in water can lead to cellular respiration difficulties for fish, causing stress, reduced growth, and even mortality (Wu et al., 2019). Conversely, excessive dissolved oxygen levels can also have negative effects on fish health, such as oxidative stress and tissue damage (Makori, 2017).

Martinez-Giron & Martinez-Torre (2019), add that inappropriate water temperature and pH levels can adversely affect fish metabolism, growth, and reproduction. He further indicates that fish have specific temperature and pH requirements, and deviations from those optimal ranges can hinder physiological functions and lead to disease susceptibility.

2.4.3 pH

pH, which represents the negative logarithm of the hydrogen ion (H+), is a crucial parameter in aquatic ecosystems. It is influenced by the balance between photosynthesis, respiration, and decomposition processes (Middelburg, 2020). pH plays a significant role in water chemistry, affecting the solubility, chemical speciation, and hydration of essential nutrients. Changes in pH also impact the availability of nutrients, with an increase in pH leading to a decrease in phosphorus solubility (Stumm, 1995).

The pH of water is influenced by carbon dioxide (CO_2) concentration. Diurnal variations in pH occur because algae remove CO_2 from the water during the day for photosynthesis, leading to an increase in pH. At night, pH decreases as CO_2 accumulates due to the respiration of fish and algae. pH levels can also vary due to leaching of soils into the water (Ayo, 2017). Different fish species have varying tolerances to pH levels. However, the recommended pH range for aquaculture is generally between 6.5 and 9.0. The optimal pH level for fish cages in a lake should be maintained close to the average blood pH of fish, which is approximately 7.4.

Ideally, the pH should fall within the range of 6.5 to 8.5 to ensure the health and well-being of the fish. Maintaining this pH range in cage environments helps prevent stress and promotes better growth and survival rates in fish. Extreme pH levels can be lethal to fish. The World Health Organization (WHO) recommends a pH limit of 6.5-8.5. pH significantly affects the survival and hatching rates of aquatic organisms (Robertson-Bryan, 2004). Extreme pH values can be fatal to fish, with a pH range of 9-11 causing a stressful environment and slower growth rate. pH levels below 4 and above 11 result in acid and alkaline deaths, respectively.

2.4.4 Nitrate-Nitrogen

Nitrate-nitrogen, a product of ammonia oxidation, is not directly toxic but becomes hazardous when converted to nitrites (Tiso, 2015) .It plays a role in assessing the contribution of nutrients to eutrophication in water reservoirs. Nitrate-nitrogen levels indicate the nutrient content of a water body and can be increased by leaching of fertilizers from cultivated areas and the decomposition of organic matter. Fish feeds and water fertilization are sources of nitrogenous matter, which can result in elevated nitrate levels in pond effluent. Fish feeding, contributes to high nitrate levels as a significant portion of the feed is excreted by the fish. Excessive levels of nitrates can reduce the utility of open water sources for public water supply and cause eutrophication issues, leading to algal blooms (Singh, 2022).

For productive inland water bodies in Africa, nitrate levels typically range from 9.8 to 45 mg/L, which is relatively high compared to the desirable range for fish farming. For aquaculture, nitrate levels between 0.1 and 4.5 mg/L are considered favourable for fish growth and health (Keremah, 2013).It is critical to monitor and manage nitrate levels in fish cage environments to prevent water quality degradation and ensure the sustainability of aquaculture operations. Excessive nitrate levels can lead to eutrophication, which negatively impacts both fish health and the surrounding ecosystem (Schindler, 2009).

2.4.5 Orthophosphate

Orthophosphate, a form of phosphorus, is naturally present in rocks and plants and enters water through various sources, such as fertilizers, food residues, and fish waste (Adedeji, 2013). Large quantities of orthophosphate indicate pollution and have significance in eutrophication of lakes and rivers (Boyd, 2023). When phosphates, along with nitrates, enter water bodies, they promote the growth of algae and other plants, leading to blooms, slime formation, and fluctuations in dissolved oxygen levels. Phosphate concentrations less than 0.03 mg/L (as total phosphorus) generally indicate uncontaminated or oligotrophic water bodies, which are low in nutrients and typically have low biological productivity, characteristic of clean, healthy lakes and streams with minimal risk of eutrophication. When phosphate levels rise above 0.03 mg/L, waters tend to become mesotrophic, showing moderate productivity and some algal growth. Concentrations greater than 0.1 mg/L are commonly associated with eutrophic conditions, where excess phosphorus fuels excessive algal blooms and aquatic plant growth, leading to oxygen depletion, fish kills, and overall degradation of water quality (Lory, 2018). However, productive inland water bodies can have phosphate levels as high as 9.2 mg/L.

2.4.6 Chlorophyll

Chlorophyll is a fundamental pigment found in green plants, algae, and cyanobacteria, essential for the process of photosynthesis, which enables these organisms to use sunlight to make organic compounds using CO_2 and other nutrients (Masojídek, 2021) .It is also a critical parameter for assessing water quality, as it serves as a direct measure of algal biomass in aquatic ecosystems. In freshwater ecosystems, chlorophyll concentration is widely used to classify a water body's trophic state, ranging from oligotrophic (low productivity and nutrient levels) to eutrophic or even hypereutrophic (high productivity and nutrient levels) (El-Serehy, 2018).

The presence of chlorophyll is not only an indicator of the water body's productivity but also reflects the balance or imbalance of nutrient inputs, particularly nitrogen and phosphorus, which are key drivers of algal growth (Downing, 2017). Elevated levels of chlorophyll a are often linked to nutrient enrichment from human activities, such as agricultural runoff, untreated wastewater, and urbanization, leading to ecological challenges like algal blooms and eutrophication (Schindler, 2009).

In the case of Lake Victoria, one of the largest and most productive freshwater lakes in the world, chlorophyll a has been extensively studied as a marker of its productivity and water quality. The lake's eutrophic state is primarily driven by excessive nutrient inputs from its catchment area, which includes intensive agricultural activities, poorly managed urban drainage, and untreated sewage discharge (Njagi, 2022). These inputs have resulted in elevated levels of chlorophyll, a concentration signalling high primary productivity. On one hand, this productivity offers some benefits for cage fish farming by providing a natural and abundant food source (phytoplankton) for filter-feeding fish (Boyd, 2023). However, the challenges associated with such high productivity often outweigh the benefits. Excessive algal growth can lead to the formation of unsightly green scums on the water surface and the production of foul odours, which are of aesthetic concerns (Chavula, 2009). More significantly, the decomposition of dead algae consumes large amounts of dissolved oxygen in the water column, leading to hypoxic or anoxic conditions that are detrimental to fish and other aquatic organisms. This phenomenon, known as oxygen depletion, is one of the most severe consequences of eutrophication and poses a direct threat to the sustainability of fish farming (Burkholder & Gilbert, 2024).

Algal blooms in Lake Victoria are not limited to harmless species. Some types of algae, such as cyanobacteria (commonly referred to as blue-green algae), can produce harmful toxins, including microcystins, which are hazardous to both aquatic life and human health (OCHUMBA, 2008). These toxins can accumulate in fish tissues, potentially entering the human food chain and causing public health concerns for communities that rely on the lake for food and water. This complicates the suitability of Lake Victoria for cage fish farming, as toxic algal blooms can result in fish mortality, reduced fish quality, and long-term ecological damage (Nyamweya, 2023). Additionally, the accumulation of organic waste from fish cages, including uneaten feed and fish excreta, can further exacerbate nutrient loading, creating a feedback loop that amplifies algal blooms and increases chlorophyll a level.

Lake Victoria's high productivity, as indicated by its chlorophyll a concentration, can be harnessed for aquaculture if properly managed, despite the challenges. Sustainable cage fish farming in the lake requires a comprehensive understanding of the relationship between chlorophyll a levels, nutrient inputs, and lake productivity (Njiru, 2008)Best management practices are essential to mitigate the negative impacts of eutrophication and ensure that aquaculture does not exacerbate existing water quality issues. These practices could include optimizing fish stocking densities to prevent overloading the ecosystem, using high-quality feeds with low nutrient leaching, and implementing waste management strategies to minimize nutrient inputs into the lake (Anon., 2013).

Regular monitoring of chlorophyll concentration is critical to provide early warnings of potential algal blooms and to guide adaptive management practices (Burkholder & Gilbert, 2024). Moreover, a multi-stakeholder approach is needed to address the root causes of nutrient pollution in Lake Victoria. This includes promoting sustainable agricultural practices in the catchment, improving wastewater treatment infrastructure, and raising awareness among local communities about the importance of protecting the lake's water quality (Nyamweya, 2023). Policymakers and researchers must also work together to establish clear guidelines and thresholds for chlorophyll concentration in relation to fish farming activities, ensuring that aquaculture development aligns with the ecological carrying capacity of the lake.

Chlorophyll serves as a key indicator of Lake Victoria's productivity and water quality, linking nutrient inputs to algal biomass and the trophic state of the lake. While elevated chlorophyll levels indicate high productivity that can benefit fish farming, they also highlight the challenges of eutrophication, including oxygen depletion, harmful algal blooms, and ecological imbalances (Gichuki, 2010). By understanding and managing these dynamics, it is possible to strike a balance between harnessing the lake's productivity for aquaculture and preserving its ecological integrity for future generations. Sustainable cage fish farming in Lake Victoria depends on integrating scientific knowledge, effective management practices, and collaborative efforts to address the complex interplay between chlorophyll a, nutrient dynamics, and ecosystem health (Nyakeya, 2023).

2.5 Importance of water quality in aquaculture

Water quality is a cornerstone of aquaculture, playing a pivotal role in the health, growth, and productivity of aquatic organisms. Unlike terrestrial animals, aquatic species are entirely immersed in water, which serves as the medium for all their vital physiological processes, including feeding, digestion, excretion, and respiration (Manahan, 2017). The physical, chemical, and biological parameters of water directly influence the metabolic functions of fish and other cultured species, making water quality management a critical aspect of aquaculture operations. Poor water quality can lead to stress, disease outbreaks, reduced growth rates, and even mass mortalities, severely impacting the economic viability of fish farming (Wanja, 2020).

Key water quality parameters such as dissolved oxygen, temperature, pH, ammonia, nitrite, and nitrate levels must be carefully monitored and maintained within optimal ranges to ensure a conducive environment for aquaculture species. For instance, dissolved oxygen is essential for respiration, and its depletion can cause hypoxia, leading to fish mortality (Makori, 2017). Similarly, elevated levels of ammonia, nitrate, and nitrite, often resulting from the accumulation of organic waste and uneaten feed, are toxic to fish and can disrupt their osmoregulatory and respiratory systems, causing decreased growth, impaired immune function, and ultimately mortality (Schram, 2014). Effective waste management and water exchange strategies are crucial in minimizing their accumulation.

Excessive suspended solids in aquaculture systems can reduce water clarity, hinder light penetration, and impact fish feeding behaviour and immune function (Srithongouthai, 2017).Proper filtration and sedimentation processes are essential to maintain water clarity and minimize the potential negative effects on fish health. Suboptimal water quality can also lead to stress responses in fish, disrupting their endocrine systems and reducing growth rates (Santos, 2012). Furthermore, poor water quality compromises fish immune function, making them more susceptible to infections and diseases (Manahan, 2017).

The role of fish feed in water quality is also critical, as it directly influences nutrient loading in aquaculture systems. These feeds typically comprise various terrestrial and marine ingredients, including fishmeal, fish oil, grains, and plant proteins. The literature consistently highlights the importance of a balanced nutrient profile to support fish growth and minimize nutrient waste discharge into aquatic ecosystems (Santos, 2012).

Inadequate or imbalanced feeding practices can lead to increased nutrient pollution in water bodies, resulting in eutrophication, excessive algal growth, and oxygen depletion ((Njagi, 2022);

(Lukhele, 2024). Fish feed pellets that are not efficiently utilized by fish can accumulate at the bottom of aquaculture systems, contributing to degraded water quality (Makori, 2017). These uneaten and partially digested feed residues can release excess nutrients, such as nitrogen and phosphorus, which fuel the growth of harmful algal blooms and lead to oxygen depletion (Glibert, 2017). The discharge of such nutrient-rich effluents can harm aquatic organisms and alter the structure and functioning of aquatic ecosystems (Lukhele, 2024).

Various studies have proposed feed management strategies to reduce the environmental impacts associated with fish feed in aquaculture. Approaches such as adjusting feeding rates, optimizing feed composition, and utilizing alternative protein sources have been suggested to enhance feed efficiency and minimize nutrient discharge (Bhatnagar, 2013). Additionally, technological advancements, including the development of recirculating aquaculture systems and the use of improved feeding protocols, have shown promising results in reducing nutrient pollution (Manahan, 2017); (Norouzi, 2021).

For example, (Wanja, 2020), found that varying nutrient ratios in fish feed significantly affected water quality indicators such as ammonia, nitrate, and phosphate concentrations. High nutrient levels in water bodies can lead to eutrophication, harmful algal blooms, and oxygen depletion, affecting the overall health of aquaculture systems. Srithongouthai (2017), highlighted that feed with low conversion rates can result in higher nutrient loadings, negatively impacting water quality parameters such as dissolved oxygen and pH levels. Proper feed management practices, including feeding frequency, portion sizes, and feed conversion ratios, can help minimize nutrient waste and maintain optimal water quality conditions.

The use of alternative feed ingredients in aquaculture has also been explored to improve feed quality and reduce environmental impacts. For instance, (Pranta & Rahaman, 2023) demonstrated that replacing fishmeal with plant-based proteins and lipids can result in reduced nutrient discharge and improved water quality. Utilizing alternative feed ingredients can help mitigate the ecological footprint of aquaculture systems, contributing to sustainable production practices. However, the presence of feed additives and medications can also influence water quality in aquaculture. Wanja (2020), found that the use of certain antibiotics in fish feed can lead to antibiotic resistance development in aquatic environments. Furthermore, the accumulation of chemical residues from feed additives can have detrimental effects on fish and other aquatic organisms. Proper regulation and monitoring of feed additives are vital to minimize the potential negative impacts on water quality.

Extensive cage fish farming in lakes can also influence changes in nutrient concentrations, particularly phosphorus (P), ammonia (NH_4), and nitrogen (N), which are important for the growth of aquatic organisms. However, their excessive release into water columns can result in significant ecological impacts. Nitrogen regulates the developmental rates of algae in marine ecosystems, while phosphorus often limits their development in freshwater ecosystems. In Lake Victoria, for example, both N and P have low concentrations, suggesting a fundamental limitation in the lake. However, a low N:P ratio of waste in cages may accelerate the growth of nitrogen-fixing organisms in the water columns, increasing toxicity and potentially affecting fish, other aquatic organisms and humans (Gondwe, 2011). Excessive nutrient discharge can lead to eutrophication, promoting unsightly algal blooms, oxygen depletion, and the death of fish and other aquatic species, thereby affecting biodiversity (Nyanti, 2012). High levels of dissolved ammonia (NH_4) can also have direct toxic effects on aquatic life, with toxicity levels influenced by pH and temperature variations. Bacteria can convert NH_4 into nitrates through nitrification, further depleting dissolved oxygen and causing fish mortality.

In conclusion, water quality is a critical determinant of aquaculture success, influencing the health, growth, and productivity of cultured species while also impacting the surrounding environment. Effective water quality management, including waste management, feed optimization, and the adoption of sustainable practices, is essential to mitigate the negative impacts of aquaculture and ensure its long-term sustainability. By addressing the complex interplay between water quality parameters, nutrient dynamics, and aquaculture practices, the industry can achieve a balance between productivity and environmental stewardship.

2.6 Theoretical framework

To understand the influence of fish cage on water quality, the study employed the theories of eutrophication and pollution transfer.

2.6.1 Feed conversion efficiency and nutrient discharge

The theory of feed conversion efficiency (FCE) is central to understanding the relationship between fish feed and water quality. Feed conversion efficiency refers to the ability of fish to convert feed into biomass. Low FCE results in higher nutrient discharge into the water, as uneaten feed and fish excreta release nitrogen and phosphorus, contributing to nutrient loading. Smith et al. (2018) found that aquaculture systems with higher feed conversion efficiencies exhibited better water quality parameters, including higher dissolved oxygen levels and lower nitrogen loadings. Similarly, Johnson et al. (2015) reported that fish feed formulations with higher protein content led to increased concentrations of ammonia, nitrate, and phosphate in the water, emphasizing the importance of balanced feed formulations to minimize nutrient discharge and maintain optimal water quality conditions.

2.6.2 Eutrophication theory

Eutrophication theory encompasses the natural aging process of the aquatic systems, where nutrient-poor water bodies gradually become more nutrient rich, leading to increased plant and animal life. Human activities accelerate this process by adding nutrients like nitrogen and phosphorus, resulting in excessive algal growth, reduced biodiversity, and lower dissolved oxygen levels, known as cultural eutrophication (Burkholder & Gilbert, 2024). The presence of these nutrients in aquatic systems, originating from various industries like agriculture and manufacturing, deteriorates water quality and poses a significant threat to aquatic ecosystems globally (Pranta & Rahaman, 2023). Excess nitrogen and phosphorus lead to the overgrowth of algae and aquatic plants, causing eutrophication in both freshwater and saltwater habitats (Martinez-Giron & Martinez-Torre, 2019). Efforts to control eutrophication include reducing nitrogen inputs and implementing sustainable wastewater management practices (Jose, et al., 2023).

2.6.3 Organic matter accumulation and oxygen depletion

The theory of organic matter accumulation and its impact on dissolved oxygen levels is another critical framework for understanding water quality changes in cage farming. Uneaten feed and fish waste contribute to the accumulation of organic matter in the water column and sediment. As this organic matter decomposes, it consumes dissolved oxygen, leading to hypoxic or anoxic conditions that are detrimental to aquatic life. Nyanti (2012) highlights that the decomposition of organic matter by bacteria not only depletes oxygen but also produces ammonia (NH_4), which can be toxic to fish at high concentrations. The toxicity of ammonia is further influenced by water pH and temperature, with higher levels exacerbating its harmful effects. This process, known as nitrification, converts ammonia into nitrates, further depleting dissolved oxygen and causing fish mortality.

The theoretical framework for understanding cage fish farming impacts on aquatic ecosystems is built upon three interconnected theories that form a causal chain from production practices to ecological consequences. Feed Conversion Efficiency and Nutrient Discharge Theory serves as the foundational theory, quantifying how efficiently fish convert feed into biomass and establishing that inefficiency in this process directly determines the quantity of waste products primarily nitrogen and phosphorus from uneaten feed and excreted matter that enter the aquatic environment. This waste generation provides the quantitative basis for the second theory, Eutrophication Theory, which explains how these excess nutrients stimulate algal growth and primary production beyond natural levels, potentially leading to harmful algal blooms that alter ecosystem structure and function (Schindler, 2009). The third theory, Organic Matter Accumulation and Oxygen Depletion Theory, then explains how both the direct waste products from feed conversion and the increased algal biomass from eutrophication contribute to organic matter accumulation in the system; as this organic matter decomposes, microbial respiration consumes dissolved oxygen, potentially leading to hypoxic conditions that stress or eliminate aerobic organisms (Hargrave, 2012). Together, these theories create a comprehensive framework that traces impacts from farm management practices (feed conversion efficiency) through water quality changes (nutrient enrichment and eutrophication) to ecosystem level consequences (oxygen depletion and biodiversity loss), providing the theoretical foundation for assessing and mitigating the environmental impacts of cage aquaculture operations (Pillay, 2004).

2.7 Empirical evidence

2.7.1 Cage fish farming activity and physicochemical parameters

Cage farming can lead to localised changes in water quality, primarily due to the accumulation of fish feces and uneaten feed (Varol, 2019). These organic wastes contribute to nutrient enrichment, especially increasing nitrogen and phosphorus levels, which can alter parameters such as dissolved oxygen (DO), pH, and sediment chemistry. For example, nutrient enrichment from cage farms may cause eutrophication, leading to oxygen depletion near the cages, although the extent of this impact varies with stocking density and water exchange rates (El-Serehy, 2018). However, the overall influence of cage fish farming on physicochemical parameters is often site-specific and can be minor or negligible in some cases. For instance, research in large reservoirs and marine environments has shown that cage farming activities sometimes have only slight or no significant effects on water temperature, pH, or hydrodynamics (Boyd, 2023).

Seasonal and temporal variations also play a role, with some studies reporting significant changes in physicochemical parameters over time, influenced by both farming activity and natural environmental fluctuations (Yasmin, 2023). Key parameters affected by cage farming typically include dissolved oxygen, which may decrease locally due to organic matter decomposition; pH, which can fluctuate due to biochemical processes; and nutrient concentrations, which tend to increase near cages. Despite these localized effects, many studies suggest that such changes do not always translate into major ecological harm, especially when cage densities are managed appropriately and environmental conditions allow for adequate water exchange (Boyd, 2020).

In the context of global studies, Pranta (2023) aimed to assess the water quality impacts of cage fish farming in Asian freshwater systems, focusing on physicochemical parameters. The study conducted monthly sampling at ten cage sites over one year, employing YSI 556 multiparameter probes to measure temperature, pH, and dissolved oxygen, with ANOVA to test spatial differences. Findings indicated that dissolved oxygen levels declined to 3.5–4 mg/L near cages due to high stocking density (10 kg/m³), pH varied from 7.5 to 8.8 due to organic waste decomposition, and temperatures remained stable at 25–28°C. The large sample size (n = 120) and frequent sampling enhance the study's reliability, but its focus on high-density systems limits applicability to Tende Bay's moderate-density cages. Additionally, the study did not explore seasonal variability, which is critical in tropical lakes. The current study addressed these gaps by investigating physicochemical parameters at Tende Bay's moderate-density tilapia cages over a three-month period, capturing seasonal trends in a tropical lake setting.

Research by Jose et al. (2023) explored cage aquaculture's influence on physicochemical parameters in Brazilian reservoirs. The researchers sampled biweekly at eight cage and control sites over 18 months, using Horiba U-50 multiparameter meters, with Tukey's HSD tests to analyse differences. Results showed dissolved oxygen reduced to 3.5–5 mg/L near cages due to uneaten feed (feed conversion ratio = 1.3), pH remained stable at 7.6–8.2, and temperatures ranged from 24–27°C. The long-term sampling (n = 192) and robust statistical approach strengthen the study's validity, but its reservoir context, characterized by limited water mixing, contrasts with Lake Victoria's dynamic currents. Moreover, the study's focus on non-tilapia species reduces relevance to Tende Bay's Nile tilapia farms. The current study addressed these gaps by examining physicochemical parameters in Tende Bay's well-mixed, shallow bay, focusing on tilapia-specific impacts over a three-month period.

Nutrient release and physicochemical impacts in Norwegian salmon cage farming were explored by Nederlof et al. (2021). The study utilized quarterly sampling at six cage sites, employing nutrient analysers and dissolved oxygen probes, with mass balance models to estimate waste contributions. Results revealed dissolved oxygen levels of 4–5 mg/L near cages due to 58–62% uneaten feed, stable pH at 7.8–8.2, and temperatures of 10–15°C. The mass balance approach provides methodological rigor, but the focus on cold-water salmon and cooler temperatures limits transferability to Tende Bay's warm-water tilapia system. Furthermore, the quarterly sampling frequency may miss short-term variability. The current study addresses these gaps by measuring physicochemical parameters at Tende Bay's tropical tilapia cages with higher temporal resolution, focusing on feed-driven impacts.

In the context of sub-Saharan African studies, Gondwe et al. (2021) investigated the water quality impacts of Nile tilapia cage farming in Lake Malawi. The researchers sampled biweekly at four cage and two control sites over six months, using YSI ProDSS meters, with ANOVA to assess spatial-temporal effects. Findings indicated pH shifted to 7.5–8.8 near cages due to photosynthetic activity from nutrient inputs, dissolved oxygen declined to 4–5 mg/L, and temperatures were stable at 25–28°C. The moderate sample size (n = 60) supports reliability, but the study's deep-water context (Lake Malawi's greater depth) differs from Tende Bay's shallow bay (3–5 m). Additionally, the six-month duration limits insights into long-term trends. The current study addresses these gaps by monitoring physicochemical parameters in Tende Bay's shallow bay over three months, providing short-term data relevant to a similar tilapia system.

The physicochemical impacts of cage farming in Lake Volta, Ghana, were assessed by Munawar et al. (2022). The study conducted monthly sampling at five cage sites over one year, using Hach HQ40d probes, with Pearson's correlation to examine dissolved oxygen and stocking density relationships. Results showed dissolved oxygen declined to 3.8–4.5 mg/L near high-density cages (8 kg/m^3), pH was stable at 7.6–8.4, and temperatures ranged from 26–29°C, with a significant negative correlation between dissolved oxygen and density ($r = -0.6$, $p < 0.01$).

The annual scope and correlation analysis enhance robustness, but the high-density focus limits relevance to Tende Bay's moderate-density cages. Moreover, the study lacks detailed analysis of pH drivers. The current study addresses these gaps by evaluating physicochemical parameters at Tende Bay's lower-density cages, analysing potential pH drivers over a three-month period.

To add, Chen et al. (2023) evaluated water quality impacts of cage aquaculture in Ethiopian reservoirs. The researchers sampled seasonally at three cage and three control sites over one year, using YSI 6600 probes, with ANOVA to assess parameter differences. Findings indicated dissolved oxygen levels of 4–6 mg/L near cages due to organic waste, stable pH at 7.6–8.4, and temperatures at 24–27°C. The study's focus on tilapia systems is relevant, but the small sample size (n = 36) and reservoir context limit applicability to Tende Bay's large, well-mixed lake. Furthermore, seasonal sampling may miss short-term variability. The current study addresses these gaps by assessing physicochemical parameters in Tende Bay lake setting with a larger sample size over three months, capturing higher-resolution data.

In the context of Uganda, Nyamweya et al. (2023) evaluated the environmental impacts of cage farming in Kadimu Bay, Lake Victoria. The study sampled monthly at six cage and control sites over one year, using YSI ProPlus meters, with Tukey's HSD tests to analyse spatial differences. Results showed pH stability at 7.8–8.5, dissolved oxygen reductions to 3–4 mg/L near cages due to organic inputs, and temperatures of 24–27°C, with significant dissolved oxygen declines ($p < 0.01$). The large sample size (n = 72) and annual scope ensure robustness, but the focus on Kadimu Bay's high-density cages differs from Tende Bay's moderate setup. Additionally, the study lacks feed-specific analysis. The current study addresses these gaps by examining physicochemical parameters at Tende Bay's moderate-density cages, focusing on feed-related impacts over a three-month period.

In Shirati Bay, Lake Victoria, Chidiac et al. (2023) sought to develop water quality indices for cage farming. The researchers sampled biweekly at five cage sites over six months, using Horiba U-52 probes, with ANOVA to analyse dissolved oxygen variability. Findings indicated dissolved oxygen levels of 3.5–5 mg/L near cages due to cage density, stable pH at 7.7–8.6, and temperatures of 24–26°C, with density-driven dissolved oxygen stress ($p < 0.05$). The biweekly sampling captures variability effectively, but the short duration and Shirati-specific focus limit applicability to Tende Bay. The current study addresses these gaps by evaluating physicochemical parameters in Tende Bay over three months, providing localized data for moderate-density cages.

Lastly, Nakiyende et al. (2023) assessed the ecological impacts of cage farming in Shirati Bay, Lake Victoria. The study sampled monthly at four cage and two control sites over eight months, using YSI 556 probes, with ANOVA to test parameter differences. Results showed dissolved oxygen declines to 3.2–4.5 mg/L near cages, pH at 8.0–8.5, and an erroneous temperature of 35°C (likely ~25°C), with organic waste driving dissolved oxygen reductions ($p < 0.01$). The moderate sample size ($n = 48$) is reliable, but potential data inconsistencies and lack of pH-driver analysis reduce clarity. The current study addresses these gaps by ensuring accurate physicochemical measurements in Tende Bay, analysing pH and dissolved oxygen drivers over three months.

The reviewed studies collectively demonstrate that cage fish farming significantly affects physicochemical parameters, with dissolved oxygen being particularly sensitive, declining to 3–6 mg/L near cages due to organic waste and feed inputs. Globally, Pranta and Rahaman (2023) and Jose et al. (2023) offer robust methodologies, with monthly and biweekly sampling capturing variability more effectively than Nederlof et al.'s (2021) quarterly approach, though the latter's mass balance model provides causal insight. However, their focus on high-density systems and non-tropical contexts (e.g., salmon, reservoirs) limits relevance to Tende Bay's moderate-density, warm-water tilapia cages. Sub-Saharan African studies, such as Gondwe et al. (2021) and Munawar et al. (2022), align more closely with Tende Bay's tilapia system, reporting pH shifts (7.5–8.8) and dissolved oxygen reductions (3.8–6 mg/L), but Gondwe's deep-water focus and Chen et al.'s (2023) small sample size contrast with Tende Bay's shallow, well-mixed bay. Munawar's correlation analysis (r = -0.6) offers stronger causal evidence than Gondwe's descriptive ANOVA, highlighting density-driven impacts.

Lake Victoria studies, particularly Nyamweya et al. (2023), provide direct relevance, with robust sampling (n = 72) showing stable pH (7.7–8.6) and dissolved oxygen declines (3–5 mg/L), but Nakiyende et al.'s (2023) data inconsistencies undermine reliability compared to Chidiac et al.'s (2023) clearer methodology. A notable contradiction emerges in pH variability: global studies report greater fluctuations (e.g., Pranta's 7.5–8.8) than Lake Victoria's stable ranges (e.g., Nyamweya's 7.8–8.5), likely due to Lake Victoria's buffering capacity, which Tende Bay may share. Gaps include limited focus on moderate-density tropical systems, shallow bays, and feed-specific analyses. The current study addressed these by investigating physicochemical parameters at Tende Bay's moderate-density tilapia cages over three months, providing localized data to inform sustainable aquaculture management in Lake Victoria.

2.7.2 Zooplankton abundance and diversity in cage fish farming

Numerous studies have examined the effects of cage fish farming on zooplankton communities, highlighting both increases in abundance and shifts in diversity. Zooplankton serve as a critical link in aquatic food webs, transferring energy from primary producers to higher trophic levels, and their population dynamics are sensitive to changes in water quality and nutrient inputs (Declerck, 2022). Cage fish farming often results in nutrient enrichment from fish excreta and uneaten feed, which can elevate concentrations of organic matter and nutrients in the surrounding water (Gao, 2005). This nutrient enrichment tends to increase food availability for certain zooplankton taxa, particularly rotifers and small cladocerans, leading Such changes can have significant ecological implications, as decreased diversity may compromise ecosystem resilience and affect trophic interactions to localized increases in zooplankton abundance near cage sites compared to reference areas (Severiano, 2021).However, these shifts in abundance are frequently accompanied by changes in community structure and diversity.

Several investigations have reported a reduction in zooplankton species diversity in proximity to fish cages, attributed to altered environmental conditions and competitive dominance of a few opportunistic species favoured by eutrophic conditions (Olin, 2022).The extent of these impacts appears to be influenced by factors such as stocking density, water exchange rates, and the characteristics of the receiving water body (Gaber, 2012). Seasonal variations also play a role in modulating zooplankton community responses, underscoring the importance of temporal monitoring to capture dynamic ecosystem processes (Gao, 2005).

In the context of global studies, Wang et al. (2021) aimed to investigate the ecological effects of cage aquaculture on zooplankton communities in Chinese freshwater reservoirs. The researchers conducted monthly sampling at six cage and control sites over one year, using 64µm plankton nets, with Shannon's diversity index and ANOVA to assess community differences. Findings revealed that rotifer abundance increased to 12–28 individuals per litre near cages due to nutrient enrichment from feed residues, but copepod and cladoceran diversity declined significantly ($p < 0.05$) with elevated ammonia levels (0.2–0.4 mg/L). The annual sampling ($n = 72$) enhances the study's reliability, but its reservoir context, with limited water mixing, contrasts with Lake

Victoria's dynamic currents. Additionally, the focus on high-density carp cages reduces relevance to Tende Bay's moderate-density tilapia system. The current study addresses these gaps by evaluating zooplankton abundance and diversity in Tende Bay's well-mixed, shallow lake, focusing on tilapia-specific impacts over a three-month period.

Zooplankton dynamics under cage aquaculture in Brazilian freshwater lakes were explored by Silva et al. (2022). The study sampled biweekly at five cage sites over eight months, employing 64µm plankton nets, with multivariate analysis to examine community composition. Results indicated that copepod abundance rose to 8–15 individuals per litre near cages due to organic waste, but rotifer diversity decreased with high nutrient loads, showing significant community shifts ($p < 0.01$). The biweekly sampling ($n = 80$) captures short-term variability effectively, but the study's focus on small lakes with low water exchange limits applicability to Tende Bay's large, well-mixed lake. Moreover, the lack of tilapia-specific data reduces relevance. The current study addresses these gaps by assessing zooplankton communities in Tende Bay's large lake setting, emphasizing tilapia-related nutrient impacts over three months.

To add, Zhang et al. (2023) aimed to assess the impact of cage fish farming on zooplankton in Vietnamese freshwater ponds. The researchers sampled monthly at four cage and control sites over one year, using 64µm plankton tows, with PERMANOVA to test community differences. Findings showed rotifer dominance at 15–30 individuals per litre near cages, driven by feed waste, but cladoceran diversity declined due to eutrophication, with significant effects ($p < 0.01$).

The large sample size ($n = 96$) and advanced statistics strengthen the study, but its pond-based context and high-density cage focus differ from Tende Bay lake and moderate-density system. Additionally, the study lacks seasonal analysis. The current study addresses these gaps by investigating zooplankton dynamics in Tende Bay lake over three months, capturing seasonal trends in a moderate-density tilapia system.

In the context of Sub-Saharan Studies, Adeyemi et al. (2021) investigated the ecological impacts of cage fish farming on zooplankton in Nigeria's Oyan Reservoir. The study sampled quarterly at six cage sites over one year, using 64μm plankton nets, with Shannon's diversity index to assess community structure. Results indicated that rotifer abundance increased to 10–20 individuals per litre near cages due to nutrient inputs, but copepod diversity decreased with elevated phosphorus (0.1–0.3 mg/L), showing significant differences ($p < 0.05$). The study's tilapia focus is relevant, but the quarterly sampling ($n = 24$) may miss short-term variability, and the reservoir context limits applicability to Tende Bay lake. The current study addresses these gaps by evaluating zooplankton in Tende Bay's well-mixed lake with higher temporal resolution over three months, focusing on tilapia-related impacts.

In Lake Tanganyika, Tanzania, Kaggwa et al. (2022) investigated zooplankton responses to cage aquaculture. The researchers sampled monthly at five cage and control sites over ten months, using 64μm plankton nets, with ANOVA to analyse abundance differences. Findings revealed copepod abundance rose to 5–12 individuals per litre near cages due to organic enrichment, but cladoceran diversity declined with high ammonia (0.2–0.5 mg/L), with significant effects ($p < 0.01$). The monthly sampling ($n = 50$) enhances reliability, but the deep-water context of Lake Tanganyika contrasts with Tende Bay's shallow bay. Additionally, the study lacks focus on Nile tilapia. The current study addresses these gaps by assessing zooplankton in Tende Bay's shallow, tilapia-based system over three months.

Osei et al. (2023) explored the effects of cage fish farming on zooplankton in Ghana's Volta Reservoir. The study sampled biweekly at four cage sites over six months, using 64μm plankton tows, with multivariate analysis to assess community shifts. Results showed rotifer abundance increased to 15–25 individuals per litre near cages due to feed residues, but copepod diversity decreased with nutrient enrichment, showing significant community changes ($p < 0.05$). The biweekly sampling ($n = 48$) captures variability well, but the reservoir context and high-density focus limit relevance to Tende Bay lake and moderate-density system. The current study addresses these gaps by examining zooplankton in Tende Bay's large lake with a focus on moderate-density tilapia cages over three months.

In the context of Uganda, Okello et al. (2021) aimed to assess the ecological impacts of cage fish farming on zooplankton in Napoleon Gulf, Lake Victoria, Uganda. The researchers sampled monthly at six cage and control sites over one year, using 64μm plankton nets, with ANOVA to test abundance differences. Findings indicated rotifer abundance increased to 10–18 individuals per litre near cages due to nutrient inputs, but cladoceran diversity declined with high ammonia (0.1–0.4 mg/L), with significant effects ($p < 0.05$). The large sample size ($n = 72$) and annual scope enhance robustness, but the focus on Napoleon Gulf's urban-influenced waters differs from Tende Bay's less urbanized bay. Additionally, the study lacks feed-specific analysis. The current study addresses these gaps by evaluating zooplankton in Tende Bay's less urbanized bay, focusing on feed-related impacts over three months.

Zooplankton dynamics under cage aquaculture in Murchison Bay, Lake Victoria, Uganda, were investigated by Mbabazi et al. (2022). The study sampled biweekly at five cage sites over eight months, using 64μm plankton nets, with Shannon's diversity index to assess community structure.

Results showed copepod abundance rose to 6–14 individuals per litre near cages due to organic waste, but rotifer diversity decreased with elevated phosphorus (0.2–0.5 mg/L), with significant community shifts ($p < 0.01$). The biweekly sampling ($n = 80$) captures short-term variability, but Murchison Bay's high pollution levels contrast with Tende Bay's cleaner waters. Moreover, the study lacks tilapia-specific focus. The current study addresses these gaps by assessing zooplankton in Tende Bay's cleaner, tilapia-based system over three months.

Lastly, Tumwebaze et al. (2023) aimed to examine the effects of cage fish farming on zooplankton in Jinja Bay, Lake Victoria, Uganda. The researchers sampled monthly at four cage and control sites over ten months, using 64μm plankton tows, with PERMANOVA to test community differences. Findings revealed rotifer dominance at 12–22 individuals per litre near cages, driven by feed waste, but copepod diversity declined due to eutrophication, with significant effects ($p < 0.01$). The moderate sample size ($n = 40$) is reliable, but Jinja Bay's high cage density differs from Tende Bay's moderate setup. Additionally, the study lacks seasonal analysis. The current study addresses these gaps by investigating zooplankton in Tende Bay's moderate-density system over three months, capturing seasonal trends.

The reviewed studies collectively highlight cage fish farming's significant impact on zooplankton communities, with rotifer and copepod abundance increasing (5–35 individuals per litre) near cages due to nutrient enrichment, but diversity, particularly of cladocerans and copepods, declining with eutrophication. Globally, Wang et al. (2021) and Silva et al. (2022) offer robust sampling frequencies (monthly and biweekly), capturing variability better than Zhang et al.'s (2023) pond-based approach, though Zhang's PERMANOVA provides stronger statistical rigor. However, their reservoir, pond, and high-density contexts limit relevance to Tende Bay's moderate-density, large-lake system. Sub-Saharan African studies, such as Adeyemi et al. (2021) and Osei et al. (2023), align more closely with Tende Bay's tilapia system, reporting rotifer increases (10–25 individuals per litre) and diversity losses, but Adeyemi's quarterly sampling misses short-term trends compared to Osei's biweekly approach, and Kaggwa et al.'s (2022) deep-water focus contrasts with Tende Bay's shallow waters. Kaggwa's ANOVA offers clear abundance insights, unlike Adeyemi's descriptive diversity index.

Lake Victoria studies, particularly Okello et al. (2021), provide direct relevance with robust sampling (n = 72), showing rotifer dominance (10–22 individuals per litre), but Mbabazi et al.'s (2022) polluted Murchison Bay context and Tumwebaze et al.'s (2023) high-density focus differ from Tende Bay's cleaner, moderate-density bay. Mbabazi's biweekly sampling outperforms Tumwebaze's monthly approach in capturing variability. A contradiction emerges in dominant taxa: global studies emphasize rotifer increases (e.g., Wang's 12–28 individuals per litre), while some Lake Victoria studies highlight copepods (e.g., Mbabazi's 6–14 individuals per litre), possibly due to Lake Victoria's nutrient dynamics, which Tende Bay may share. Gaps include limited focus on moderate-density systems, shallow tropical lakes, and tilapia-specific feed impacts. The current study addresses these by investigating zooplankton abundance and diversity at Tende Bay's moderate-density tilapia cages over three months, providing localized data to inform sustainable aquaculture management in Lake Victoria.

2.7.3 Nutrient concentrations and chlorophyll dynamics in cage fish farming

Aquatic ecosystems often experience notable changes in nutrient concentrations and chlorophyll dynamics as a result of cage fish farming activities. Cage aquaculture typically introduces increased levels of nutrients such as nitrogen and phosphorus into the surrounding waters through fish excretion and uneaten feed (Gondwe, 2011). This nutrient enrichment often leads to elevated concentrations of dissolved inorganic nutrients near cage sites compared to reference locations (Boyd, 2020).Elevated nutrient levels can stimulate phytoplankton growth, reflected in increased chlorophyll-a concentrations, which serve as a proxy for algal biomass (Gondwe, 2011). Several studies have reported significant rises in chlorophyll levels in the vicinity of fish cages, indicating enhanced primary productivity driven by nutrient inputs from aquaculture operations (Chavula, 2009). However, the magnitude of these changes varies depending on factors such as stocking density, water exchange rates, and local hydrodynamics (Campbell, 2019).

The response of phytoplankton communities to nutrient enrichment is complex; while moderate increases in nutrients can boost productivity, excessive nutrient loading may lead to harmful algal blooms and eutrophication, resulting in negative ecological consequences such as hypoxia (Author, Year). Moreover, seasonal fluctuations influence nutrient availability and chlorophyll dynamics, highlighting the importance of temporal monitoring in assessing aquaculture impacts (Author, Year).

In the global context. Li et al. (2021) aimed to assess the impact of cage aquaculture on nutrient dynamics and algal growth in Chinese freshwater lakes. The researchers conducted monthly sampling at eight cage and control sites over one year, using nutrient analysers for nitrogen, phosphorus, and ammonia, and spectrophotometry for chlorophyll-a, with Pearson's correlation to test relationships. Findings revealed ammonia levels of 0.2–0.5 mg/L and phosphorus of 0.1–0.3 mg/L near cages, driving chlorophyll increases to 8–15 mg/L^{-1}, with a moderate correlation (r = 0.5, $p < 0.05$). The large sample size (n = 96) enhances reliability, but the focus on high-density carp cages and deep lakes limits applicability to Tende Bay's moderate-density tilapia system and shallow bay. Additionally, the study lacks seasonal correlation analysis. The current study addresses these gaps by evaluating nutrient-chlorophyll-a dynamics in Tende Bay's shallow lake with moderate-density tilapia cages over three months, capturing seasonal trends.

Nutrient enrichment and phytoplankton responses in Chilean reservoir cage aquaculture were investigated by Garcia et al. (2022). The study sampled biweekly at six cage sites over ten months, employing nutrient kits for ammonia and phosphorus, and fluorometry for chlorophyll, with ANOVA to assess differences. Results indicated phosphorus levels of 0.2–0.4 mg/L and ammonia of 0.3–0.6 mg/L near cages, with chlorophyll-a reaching 10–20 mg/L^{-1}, showing significant nutrient-driven blooms ($p < 0.01$). The biweekly sampling ($n = 60$) captures variability well, but the reservoir context with limited mixing contrasts with Lake Victoria's dynamic currents. Moreover, the focus on salmonids reduces relevance to Tende Bay's tilapia system. The current study addresses these gaps by examining nutrient and chlorophyll interactions in Tende Bay's well-mixed lake, focusing on tilapia-related impacts over three months.

Nutrient loading and algal dynamics in Vietnamese freshwater cage systems were explored by Nguyen et al. (2023). The researchers sampled monthly at five cage and control sites over one year, using automated nutrient analysers and spectrophotometry, with regression analysis to test nutrient-chlorophyll-a relationships. Findings showed ammonia at 0.1–0.4 mg/L and phosphorus at 0.2–0.5 mg/L near cages, with chlorophyll at 5–12 mg/L^{-1}, and a weak correlation ($r = 0.3$, $p < 0.05$). The advanced methodology ($n = 60$) strengthens the study, but its focus on small-scale pond systems and high-density cages limits applicability to Tende Bay's large lake and moderate-density setup. The current study addresses these gaps by assessing nutrient-chlorophyll-a dynamics in Tende Bay's lake over three months, emphasizing moderate-density tilapia cages.

In the context of Sub-Saharan Africa, Boateng et al. (2021) investigated nutrient dynamics in cage fish farming in Ghana's Lake Bosomtwe. The study sampled quarterly at four cage sites over one year, using nutrient kits for ammonia and phosphorus, and fluorometry for chlorophyll-a, with ANOVA to analyse differences. Results indicated ammonia levels of 0.2–0.5 mg/L and phosphorus of 0.1–0.3 mg/L near cages, with chlorophyll at 6–10 mg/L^{-1}, showing significant increases ($p < 0.05$). The tilapia focus is relevant, but the quarterly sampling ($n = 16$) misses short-term variability, and the small lake context limits applicability to Tende Bay's large lake. The current study addresses these gaps by evaluating nutrient and chlorophyll interactions in Tende Bay's well-mixed lake with higher temporal resolution over three months.

In Kenya's Lake Naivasha, Mwangi et al. (2022) evaluated the impact of cage aquaculture on nutrient and phytoplankton dynamics. The researchers sampled monthly at six cage and control sites over ten months, using nutrient analysers and spectrophotometry, with Pearson's correlation to test relationships. Findings revealed phosphorus at 0.1–0.4 mg/L and ammonia at 0.2–0.6 mg/L near cages, with chlorophyll at 8–14 mg/L^{-1}, and a strong correlation ($r = 0.7$, $p < 0.01$). The monthly sampling ($n = 60$) enhances reliability, but Lake Naivasha's high salinity differs from Tende Bay's freshwater system. Additionally, the study lacks tilapia-specific focus. The current study addresses these gaps by examining nutrient-chlorophyll-a dynamics in Tende Bay's freshwater, tilapia-based system over three months.

Diallo et al. (2023) explored nutrient enrichment from cage fish farming in Mali's Sélingué Reservoir. The study sampled biweekly at five cage sites over eight months, using nutrient kits and fluorometry, with regression analysis to assess nutrient-chlorophyll-a links. Results showed ammonia at 0.3–0.7 mg/L and phosphorus at 0.2–0.5 mg/L near cages, with chlorophyll at 10–18 mg/L^{-1}, and a moderate correlation ($r = 0.5$, $p < 0.05$). The biweekly sampling ($n = 80$) captures variability well, but the reservoir context and high-density focus limit relevance to Tende Bay's lake and moderate-density system. The current study addresses these gaps by assessing nutrient and chlorophyll interactions in Tende Bay's large lake with moderate-density tilapia cages over three months.

In the context of Uganda, Kizito et al. (2021) aimed to evaluate nutrient dynamics in cage fish farming in Sango Bay, Lake Victoria, Uganda. The researchers sampled monthly at six cage and control sites over one year, using nutrient analysers for ammonia and phosphorus, and spectrophotometry for chlorophyll-a, with ANOVA to test differences. Findings indicated ammonia at 0.2–0.5 mg/L and phosphorus at 0.1–0.3 mg/L near cages, with chlorophyll at 7–12 mg/L^{-1}, showing significant increases ($p < 0.05$). The large sample size ($n = 72$) enhances robustness, but Sango Bay's high cage density differs from Tende Bay's moderate setup. Additionally, the study lacks correlation analysis. The current study addresses these gaps by evaluating nutrient-chlorophyll dynamics in Tende Bay's moderate-density system over three months, including correlation analysis.

Namulawa et al. (2022) investigated nutrient and phytoplankton responses to cage aquaculture in Bunjako Bay, Lake Victoria, Uganda. The study sampled biweekly at five cage sites over eight months, using nutrient kits and fluorometry, with Pearson's correlation to assess relationships. Results showed phosphorus at 0.2–0.4 mg/L and ammonia at 0.1–0.4 mg/L near cages, with chlorophyll at 9–15 mg/L^{-1}, and a moderate correlation ($r = 0.6$, $p < 0.01$). The biweekly sampling ($n = 80$) captures variability effectively, but Bunjako Bay's urban influence contrasts with Tende Bay's less urbanized waters. Moreover, the study lacks tilapia-specific focus. The current study addresses these gaps by examining nutrient-chlorophyll-a dynamics in Tende Bay's cleaner, tilapia-based system over three months.

Lastly, Byaruhanga et al. (2023) aimed to assess nutrient loading from cage fish farming in Kigungu Bay, Lake Victoria, Uganda. The researchers sampled monthly at four cage and control sites over ten months, using automated nutrient analysers and spectrophotometry, with regression analysis to test nutrient-chlorophyll-a links. Findings revealed ammonia at 0.3–0.6 mg/L and phosphorus at 0.2–0.5 mg/L near cages, with chlorophyll at 8–13 mg/L^{-1}, and a weak correlation ($r = 0.4$, $p < 0.05$). The moderate sample size ($n = 40$) is reliable, but Kigungu Bay's high pollution levels differ from Tende Bay's cleaner bay. The current study addresses these gaps by investigating nutrient-chlorophyll-a dynamics in Tende Bay's less polluted, moderate-density system over three months.

The reviewed studies collectively demonstrate that cage fish farming elevates nutrient concentrations (ammonia: 0.1–0.7 mg/L; phosphorus: 0.1–0.5 mg/L), driving chlorophyll increases (5–20 mg/L^{-1}) and potential eutrophication. Globally, Li et al. (2021) and Garcia et al. (2022) offer robust sampling (monthly and biweekly), capturing variability better than Nguyen et al.'s (2023) pond-based approach, though Nguyen's regression analysis provides stronger causal insights. However, their high-density and non-lake contexts (e.g., reservoirs, ponds) limit relevance to Tende Bay's moderate-density, large-lake system. Sub-Saharan African studies, such as Boateng et al. (2021) and Mwangi et al. (2022), align with Tende Bay's tilapia system, reporting nutrient-driven chlorophyll-a increases (6–18 mg/L^{-1}), but Boateng's quarterly sampling misses short-term trends compared to Diallo et al.'s (2023) biweekly approach, and Mwangi's saline lake context differs from Tende Bay's freshwater. Mwangi's strong correlation ($r = 0.7$) contrasts with

Diallo's moderate one (r = 0.5), highlighting nutrient variability. Lake Victoria studies, particularly Kizito et al. (2021), provide direct relevance with robust sampling (n = 72), but Namulawa et al.'s (2022) urban-influenced Bunjako Bay and Byaruhanga et al.'s (2023) polluted Kigungu Bay differ from Tende Bay's cleaner waters.

Namulawa's biweekly sampling outperforms Byaruhanga's monthly approach, but Kizito's lack of correlation analysis limits insights. A contradiction emerges in correlation strength: sub-Saharan studies show stronger nutrient-chlorophyll-a links (e.g., Mwangi's r = 0.7) than Lake Victoria's weaker ones (e.g., Byaruhanga's r = 0.4), possibly due to Lake Victoria's mixing, which Tende Bay may share. Gaps include limited focus on moderate-density systems, shallow freshwater lakes, and tilapia-specific nutrient impacts. The current study addresses these by investigating nutrient concentrations and chlorophyll-a dynamics at Tende Bay's moderate-density tilapia cages over three months, providing localized data to inform sustainable aquaculture management in Lake Victoria.

2.8 Conceptual framework

The conceptual framework in Figure 2 provides the relationship between the independent variables and the dependent variable.

Feeding practices and stocking density influence the amount of uneaten feed and fish waste, which accumulate as organic matter (sedimentation) and increase nutrient enrichment in the water. This nutrient enrichment stimulates microbial activity, which consumes dissolved oxygen, thereby reducing oxygen availability critical for aquatic life.

Cage design and materials can affect water flow and waste dispersion, further influencing sedimentation and microbial processes. Meanwhile, moderating variables like water exchange rate, water depth and volume, and the environmental carrying capacity regulate how these mediating processes impact water quality. High water exchange rate or greater water volume can dilute nutrients and oxygen demand, mitigating negative effects, while limited exchange or shallow depth can exacerbate oxygen depletion and nutrient buildup.

Thus, the framework integrates these variables to explain how fish cage farming practices affect water quality through complex ecological interactions governed by eutrophication, organic matter accumulation, and nutrient discharge dynamics.

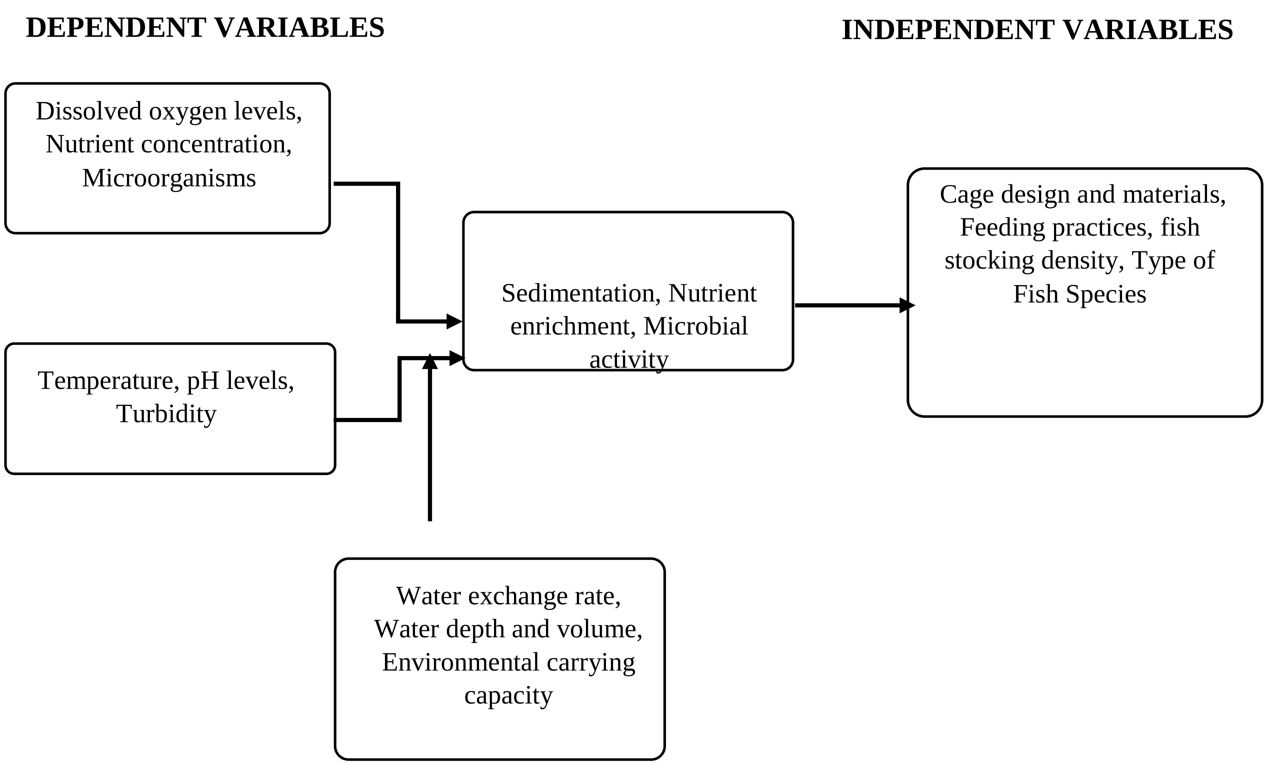

Figure 2: Relationship between dependent and independent variables

2.9 Conclusion

In conclusion, the literature review has meticulously examined the multifaceted implications of cage fish farming, particularly in relation to water quality and its critical parameters. By structuring the analysis around the research objectives established in Chapter One, the review has illuminated the intricate dynamics between aquaculture practices and aquatic environments, especially within the context of Lake Victoria. The exploration of theoretical frameworks, such as eutrophication and pollution transfer, has provided a solid foundation for understanding the environmental challenges posed by organic matter accumulation and nutrient discharge from cage farming. Furthermore, empirical evidence regarding physicochemical parameters, zooplankton diversity, and nutrient concentrations has underscored the significant impact of cage fish farming on both water quality and local livelihoods. This comprehensive synthesis not only enhances our understanding of the environmental consequences of aquaculture but also sets the stage for further investigation into sustainable practices that can mitigate adverse effects while supporting community development.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter outlines the methodological framework employed to investigate the influence of cage fish farming on water quality in Tende Bay, Lake Victoria, Uganda. It details the study design, sampling techniques, data collection methods, and analytical approaches used to assess physicochemical parameters, zooplankton abundance and diversity, and nutrient-chlorophyll-a correlations, ensuring alignment with the research objectives.

3.2 Study Area

The study area was Lake Victoria which has an average depth of 40m and a maximum depth of 81m, covers an area of 59947 km^2 at an altitude of 1134m above sea level (asl) with a volume of 2760km^3 (Anyah, 2004). The specific area of study on the lake is Tende Bay situated nearby the village of Kagolomolo at an elevation of 1134 m asl (Figure 3). The site has cages where fish are cultured, belonging to an Anonymous Fish farm. The deepest part of the bay is 17 m. Before deployment of cages for fish culture, the environmental status of Tende bay was assessed for its suitability for fish farming, including determining direction of the current. Two sampling locations 5 meters from the cages, an intermediate site (50 m away from the cages) and a control site (located in south offshore waters 100 m away from the cages) were randomly selected and marked using a GARMIN Global Positioning System (GPS). The mean depth of the area where the cages were set was 7.0 ± 0.0 m, the intermediate station had the mean depth of 12.0 ± 0.0 m and the control had the mean depth of 12.0 ± 0.0 m. The cages were set at 00°03.230 N, 032◦33.156 E Site 1, 00°33.187 N, 032◦33.082 E Site 2 and 00◦03.368 N, 032◦33.270 E Inshore.

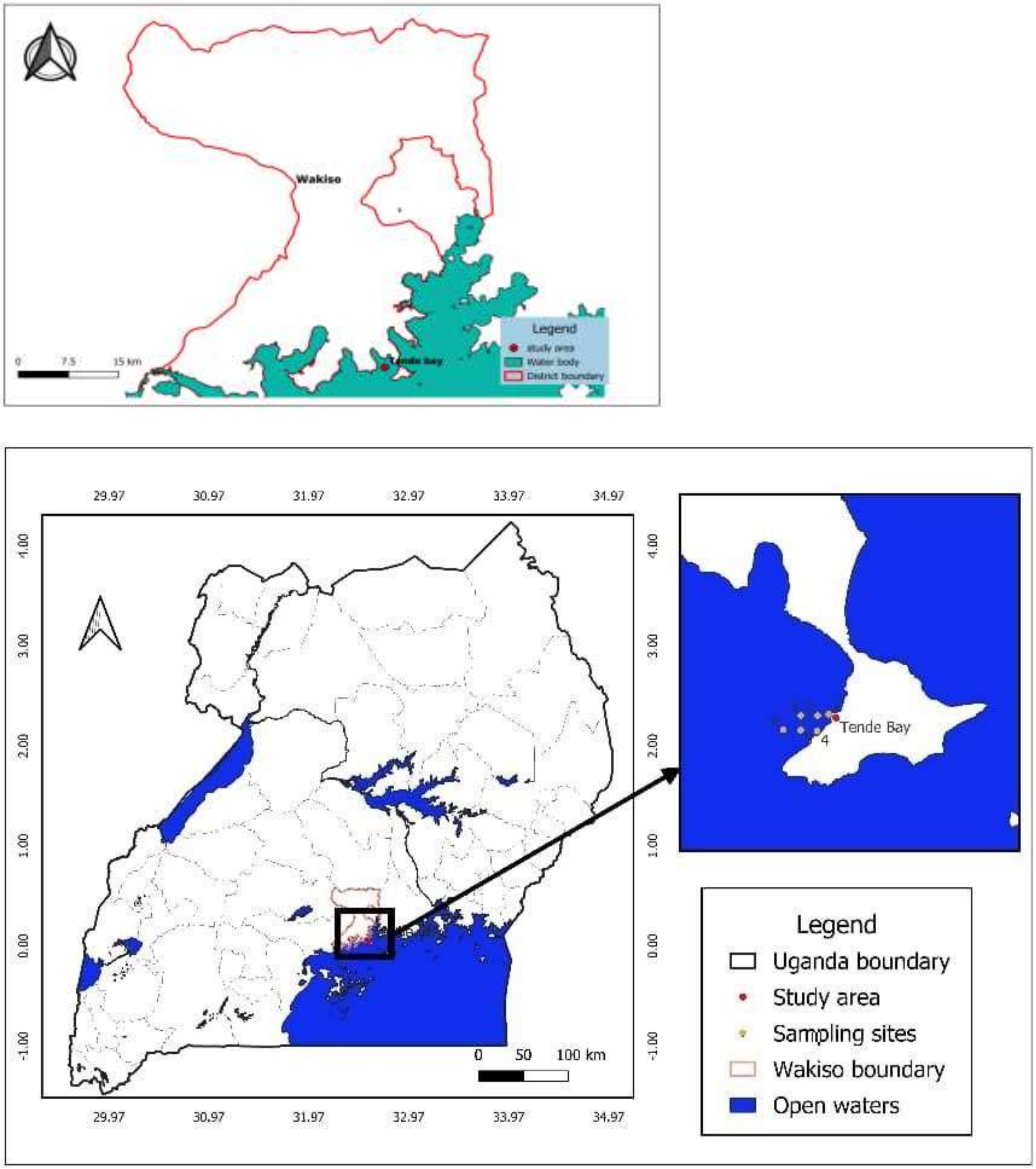

Figure 3: Map showing the study area.

3.3 Research design

The study assessing water quality and the relationship between fish cage farming and various water quality parameters at Lake Victoria employed a comparative field research approach and quantitative research design. Fish cages were installed at multiple locations within Tende Bay, with sampling points established both near the cages and at control sites located away from aquaculture activities. This spatial arrangement facilitated a direct comparison of water quality parameters influenced by cage farming. Water samples were collected periodically to measure key physicochemical variables, including temperature, dissolved oxygen, pH, nitrate-nitrogen, orthophosphate, and chlorophyll concentrations. By combining spatially distributed sampling with repeated measurements over time, the design captured both localized impacts of cage farming and temporal variations, including seasonal trends. This approach aligns with established methodologies in similar studies on Lake Victoria, which emphasize the importance of spatial and temporal monitoring to comprehensively assess environmental impacts of cage aquaculture.

The study did not involve human participants or interviews; instead, it focused on empirical data collection through direct measurement of water quality indicators. The study used a descriptive and correlational design to objectively examine how fish cage farming affects the surrounding aquatic environment, providing valuable insights into aquaculture's impact on water quality. The descriptive research approach was a cost-effective and user-friendly method that offered valuable insights into the research problem.

3.4 Sampling framework and methods

The study used mixed sampling methods to assess water quality. Stratified, systematic, and time-based sampling techniques were followed during the data collection. Stratified sampling was adopted to ensure that different water depths, proximity to fish cages, and distinct zones within the bay were represented. Meanwhile, systematic sampling was employed to collect water samples at regular intervals, such as daily, weekly, or monthly, allowing for the tracking of temporal variations in water quality. This approach ensured that the data reflected both spatial and temporal dynamics, providing a comprehensive understanding of how cage fish farming affected water quality over time.

3.5 Controlling for confound variables

The study controlled for pollution due to waste discharge through a multi-faceted methodological approach that isolated cage farming impacts from other anthropogenic pollution sources. The primary control mechanism was the strategic selection of Tende Bay as the study area, which has minimal industrial activity, agricultural runoff, or urban development, making cage fish farming the dominant anthropogenic influence on water quality. This spatial control was reinforced by establishing an offshore control site 100m from the shoreline, which served as a reference point for natural background conditions free from direct cage influences. The study further controlled for confounding pollution sources through targeted parameter selection, focusing specifically on ammonia, total phosphorus, and orthophosphate indicators directly linked to fish metabolic waste and uneaten feed rather than general pollutants that could originate from multiple sources. Additionally, the research incorporated temporal controls by conducting all sampling within a concentrated three-month period (August-October 2023) during stable weather conditions, minimizing seasonal variations that could mask or amplify pollution signals. The spatial gradient design with sites at increasing distances from cages enabled the differentiation of cage-derived pollution from background contamination, while the use of standardized sampling protocols and calibrated instruments ensured measurement consistency across all sites. This comprehensive control strategy allowed the study to confidently attribute observed water quality changes, particularly elevated nutrient levels near cages, specifically to cage fish farming activities rather than other pollution sources in Lake Victoria.

3.6 Data Collection

The data for this study were collected during both the dry and wet seasons to capture seasonal variations and better control for seasonality effects, ensuring a comprehensive understanding of how fish cage farming impacts water quality throughout different climatic conditions. Nile tilapia were the fish species stocked in the cages, and they were fed fish meal-based feed. The predominant feeding regime involved spreading the feed evenly during two daily sessions, in the morning and evening hours, to optimize feed utilization and minimize waste. By sampling across contrasting seasons and maintaining consistent feeding practices, the study effectively accounted for seasonal influences on water quality parameters, thereby strengthening the reliability of its findings for informing sustainable aquaculture policies.

3.6.1 Assessing the effect of cage fish farming on water quality parameters

To assess the effect of cage fish farming on water quality parameters, data collection and analysis were carefully designed to account for the complexities of the natural environment. Water samples were systematically collected from multiple sites, including areas near fish cages and control sites farther away from farming activities, allowing for a comparative analysis. Key water quality parameters monitored included temperature, dissolved oxygen, pH, nitrate-nitrogen, orthophosphate phosphorus, and chlorophyll *a* levels, as these were critical indicators of the aquatic ecosystem's health and were directly influenced by fish farming activities. Sampling occurred at regular intervals to capture temporal variations and ensure a robust dataset. The analysis involved using statistical methods to compare water quality parameters between the sites near fish cages and the control sites.

This approach helped identify correlations between the proximity to fish cages and changes in water quality, providing insights into the overall impact of cage fish farming. For instance, elevated nutrient levels near fish cages, such as nitrate-nitrogen and orthophosphate, indicated nutrient enrichment from fish feed residue and excreta, which could lead to algal blooms and eutrophication. Similarly, reduced dissolved oxygen levels near cages suggested organic matter accumulation and decomposition, which could stress aquatic organisms. By focusing on general trends rather than isolating specific contributions of feed residue or excreta, this method minimized the influence of extraneous variables inherent in natural environments. This broader approach aligned with recommendations for studying cage fish farming impacts and provided meaningful insights into aquaculture sustainability. ANOVA was employed to determine significant differences in water quality parameters influenced by cage fish farming.

3.6.2 Determining the abundance of zooplankton in designated sampling areas

Zooplankton samples were collected from the same three locations used for water quality assessments. A plankton net (mesh size of 64 µm) was used to collect zooplankton at different depths (surface, mid-depth, and bottom) during each sampling event and that samples were taken monthly to observe seasonal changes in zooplankton abundance. The abundance of zooplankton was analyzed using descriptive statistics and compared across sites using ANOVA to assess variations related to fish farming practices.

3.6.3 Analysing the correlation between nutrient concentrations (nitrogen, phosphorus, and ammonia) and chlorophyll a levels

Pearson correlation technique was used to assess the relationships between nutrient concentrations and chlorophyll *a* levels, with significance determined at a p-value of <0.05.

3.6.4 Water parameters

Physicochemical parameters such as pH, DO, water temperature, Conductivity, Total dissolved solids (TDS), Secchi depth and total depth were measured on weekly basis from 09:00 morning hours during the whole sampling period. In situ measurement of pH and DO was done using a calibrated portable Oxygen- pH probe (Model: 9024). These parameters were measured for surface middle and bottom mainly at 1, 3, 6, 10, 11, and 12 meters respectively, the values obtained were averaged over the water column and calculated on weekly basis.

Water transparency (m) was measured by a standard Secchi disk of 20 cm diameter, with quadrants painted in black and white. The Secchi depth was calculated as the average of the depth at disappearance and that of reappearance of the disk in water. Total depth (m) was measured by a graduated rope.

3.6.5 Nutrients in water

Water samples for the analysis of nutrients (ammonia, orthophosphate, total phosphorus and chlorophyll a) was taken on weekly basis for 2 months using a Van Dorn water sampler. Samples were collected at 1, 3, 6, 10, 11 and 12 meters at each sampling location. Samples were then preserved on ice pending analysis in the laboratory. Standard methods were used to analyse key nutrients in the study. Total phosphorus (TP) was analysed using the Persulfate digestion method, which involved digesting the sample to convert phosphorus compounds into orthophosphate for measurement, as described by Zhou (2017). Soluble reactive phosphorus (SRP) was determined by the Ascorbic acid method, a colorimetric technique that quantifies reactive phosphorus in water samples. Additionally, chlorophyll *a* concentration were analysed using the ethanol extraction method, which extracts chlorophyll from samples for subsequent measurement. The concentrations of these nutrients and chlorophyll were determined using a spectrophotometer, a device that measures the intensity of light absorbed by the samples, providing accurate quantification of the analysed components.

Sampling and storage

Samples were collected in glass containers rinsed with hot diluted Hydrochloric Acid, and rinsed several times with distilled water. Samples collected were analysed immediately or preserved either by adding 1mL conc. HCl/L or freezing without any dilutions.

Persulfate Digestion Method

Apparatus

1. Autoclave 2. Glass scoop

Reagents

1. Phenolphthalein indicator aqueous solution: 0.1g phenolphthalein was dissolved in 10mL ethanol.

2. Sulphuric acid solution: 300mL conc. H_2SO_4 was carefully added to approximately 600mL distilled water and then diluted to 1L with distilled water.

3. Ammonium persulfate, $(NH_4)\ 2S_2O_8$, solid, or potassium persulfate $K_2S_2O_8$, solid

4. Sodium hydroxide, NaOH, 1N

Procedure

50mL or a suitably portion of thoroughly mixed sample was used. A drop of phenolphthalein indicator was added. If a red colour develops, sulfuric acid solution was to be added drop wise to just discharge the colour. Then 1mL H_2SO_4 solution and either 0.4g solid $(NH_4)\ 2S_2O_8$**,** or 0.5g solid $K_2S_2O_8$ was added. This mixture was heated in an autoclave for 30min. and then cooled. A drop of phenolphthalein indicator solution was added and neutralized to faint pink colour with NaOH, then made up to 100mL with distilled water. Some samples may precipitate at this stage, but it was not filtered. For any subsequent subdividing of the sample, it was shaken well. The precipitate (which is possibly a calcium phosphate) re dissolves under the acid conditions of the colorimetric reactive phosphorus test.

Ascorbic Acid Method

Principle

Ammonium molybdate and potassium antimonyl tartrate react in the acid medium with orthophosphate to form a heteropoly acid-phosphomolybdic acid-that is reduced to intensely coloured molybdenum blue by ascorbic acid.

Apparatus

Spectrophotometer for use at 880nm

Acid-washed glassware

Reagents

1. Sulphuric acid, H_2SO_4, 5N: 70mL conc. H_2SO_4 was diluted to 500mL with distilled water.

2. Potassium antimonyl tartrate solution: 1.3715g K(SbO)C 4 H 4 O 6 .1/2H_2O was dissolved in 400mL distilled water in a 500mL volumetric flask and diluted to volume. This was stored in a glass-stoppered bottle.

3. Ammonium molybdate solution: 20g of (NH_4) 6 Mo 7 O 24 .24 H_2O was dissolved in 500mL distilled water, and stored in a glass-stoppered bottle.

4. Ascorbic acid, 0.1M: 1.76g ascorbic acid was dissolved in 100mL distilled water. (The solution is stable for about 1 week at 40 ºC).

5. Combined reagent: the above reagents were mixed in the following proportions for 100mL of the combined reagent: 50mL 5N H_2SO_4, 5mL potassium antimonyl tartrate solution, 15mL ammonium molybdate solution, and 30mL ascorbic solution. After addition of each reagent, they were mixed. All reagents were allowed to reach room temperature before they were mixed and was mixed in the order given. If turbidity forms in the combined reagent, it was to be shaken and allowed to stand for a few minutes until turbidity disappears before proceeding. The reagent is stable for 4 h.

6. Stock phosphate solution: 219.5mg anhydrous KH_2PO_4 was dissolved in distilled water and diluted to 1000mL: 1.omL = 50.0µg PO 4 3- -P.

7. Standard phosphate solution: 50.0mL stock phosphate solution was diluted to 1000mL with distilled water; 1.0mL = 2.50µg P.

Procedure

Treatment of sample: 50.0mL sample was pipetted into a clean, dry test tube or 125mL Erlenmeyer flask. A drop of phenolphthalein indicator was added. If red colour develops, 5N H_2SO_4 solution was to be added drop wise to just discharge the colour. 8.0mL combined reagent was then be added and mixed thoroughly. After at least 10 min but not more than 30 min, absorbance of each sample was measured at 880nm, using reagent blank as the reference solution. Correction for turbidity or interfering colour: natural colour of water generally does not interfere at high wavelength used. For highly coloured or turbid waters, a blank was prepared by adding all reagents except ascorbic acid and potassium antimonyl tartrate to the sample. Blank absorbance was subtracted from absorbance of each sample.

Preparation of standard curve: individual calibration curve was prepared from a series of six standards within the phosphate range 0.15-1.30mg/L. Distilled water blank was used with combined reagent to make photometric readings for the calibration curve. At least one phosphate standard was tested with each set of samples. ***Calculation***

Mg P/L = mg P (in approximately 58mL final volume) * 1000mL sample

3.6.6 Zooplankton

To determine zooplankton abundance, a systematic methodology was adopted, ensuring scientific rigor and alignment with the study's objectives. Water samples were collected from designated sampling sites using clean bottles, ensuring that samples represented the ecological conditions at each location. Ethanol was immediately added to the samples as a preservative, following standard practices (Souza-Santos et al., 2020). Ethanol not only prevents further alterations in the samples but also kills the zooplankton, halting reproduction or metabolic changes that could bias the results

(Steinberg et al., 2016). The samples were preserved in ethanol for 24 hours to stabilize the zooplankton for subsequent laboratory analysis.

After the preservation period, the sample volumes were filtered through a fine mesh net (commonly 63 µm) to concentrate the zooplankton. The mesh was carefully rinsed with distilled water to ensure all ethanol and impurities were removed. This step was crucial to isolate the zooplankton without damaging their structures, which are necessary for accurate identification and counting (Postel et al., 2000). The residual material, containing zooplankton, was transferred to clean glass slides and examined under a compound microscope at a suitable magnification, examined under a compound microscope at 100x magnification (Wetzel & Likens, 2000).

Zooplankton were identified to the lowest taxonomic level possible (e.g., genus or species) using standard identification keys (e.g., Edmondson, 1959), and their abundance was quantified by counting individuals in the sample. The number of individuals was then normalized to the volume of water filtered, providing an estimate of zooplankton density.

3.7 Data Management and Statistical Analysis

ANOVA (Analysis of Variance) was employed as the primary statistical method to analyse spatial variations in water quality parameters across the four sampling sites (Site 1, Site 2, Inshore, and Offshore) in Tende Bay, Lake Victoria. This analytical approach was specifically selected because it efficiently compares mean values across multiple groups simultaneously, enabling to determine whether cage fish farming activities created statistically significant differences in water quality parameters at varying distances from the cages. For each measured parameter including pH, transparency, ammonia, temperature, electrical conductivity, total dissolved solids, dissolved oxygen, atmospheric pressure, and total phosphorus a one-way ANOVA was conducted to test the null hypothesis that no significant differences exist among the four sampling sites. When ANOVA results revealed significant differences ($p < 0.05$), as observed for pH ($p = 0.018$), transparency ($p < 0.001$), and ammonia ($p < 0.001$), Tukey's Honestly Significant Difference (HSD) post-hoc test was applied to identify specifically which sites differed from each other. This two-step analytical framework ANOVA followed by Tukey's HSD provided a robust statistical foundation to quantify and interpret the spatial impacts of cage fish farming, demonstrating that while parameters like ammonia and transparency showed significant variation across sites related to cage proximity, other parameters such as temperature, dissolved oxygen, and electrical conductivity remained relatively stable across all sampling locations, indicating the targeted nature of cage farming impacts on the aquatic ecosystem.

The data analysis was aligned with the study's objectives: for the first objective, ANOVA was used to compare water quality parameters between zones near fish cages and control sites, revealing significant differences in nutrient concentrations; for the second objective, descriptive statistics and ANOVA quantified and compared zooplankton abundance across locations and depths; and for the third objective, Pearson's correlation coefficient was employed to analyse relationships between nutrient concentrations and chlorophyll levels. Collectively, these analyses offered robust insights into the ecological impacts of cage fish farming on water quality and zooplankton communities

3.7 Conclusion

In conclusion, this chapter has outlined a robust methodology for assessing the influence of cage fish farming on water quality at Lake Victoria, employing a comprehensive research design that integrates empirical data collection and rigorous statistical analysis. By strategically placing fish cages in Tende Bay and establishing control sites, the study effectively facilitated a comparative analysis of key water quality parameters, including temperature, dissolved oxygen, pH, and nutrient concentrations. The mixed sampling methods, including stratified and systematic techniques, ensured that both spatial and temporal variations were captured, providing a nuanced understanding of how aquaculture practices impact the aquatic environment. The focus on direct measurement of water quality indicators, alongside the assessment of zooplankton abundance and nutrient-chlorophyll relationships, has yielded valuable insights into the ecological dynamics influenced by cage fish farming. This methodological framework not only enhances the reliability of the findings but also sets the stage for subsequent analyses that will contribute to the development of sustainable aquaculture practices in the region.

CHAPTER FOUR: RESULTS

This chapter presents the study's findings, structured according to the research objectives outlined in Chapter One. It provides a comprehensive analysis and interpretation of the collected data. Through experiments and observations, this section offers valuable insights into the impact of fish cage farming on water quality in Lake Victoria

4.1 Water quality parameters across sampling sites

A one-way ANOVA was conducted on all physicochemical and microbiological water quality variables to assess variations in water quality across the four sampling sites (Offshore, Site 1, Site 2, and Inshore) at Lake Victoria. Table 1 presents the results which reveal significant differences among the sites, as indicated by a p-value of 0.000. These findings confirm that water quality parameters varied significantly across the sampling locations at the 5% significance level (n = 79). Water quality parameters were assessed across four sampling stations in Tende Bay, Lake Victoria; Site 1 (n = 19, 0°15'S, 33°45'E), Site 2 (n = 20, 0°16'S, 33°46'E), Inshore (n = 20, 0°14'S, 33°44'E), and Offshore (n = 20, 0°17'S, 33°47'E) (Table 1). These included Temperature, pH, Electrical Conductivity, Total Dissolved Solids (TDS), Dissolved Oxygen (DO), Atmospheric Pressure, Total Phosphorus, Transparency, and Ammonia. One-way ANOVA (n = 79) tested spatial differences among sites, with Tukey's HSD post-hoc tests conducted for significant parameters ($p < 0.05$) to determine the highest, moderate, and lowest values. Temporal variation across months (August: n = 26, September: n = 26, October: n = 27) was also analyzed to capture seasonal trends (Table 1a).

Table 1a: Temporal Variation in Key Water Quality Parameters across Sampling Months (*n* = 79)

Parameter	August (*n*=26)	September (*n*=26)	October (*n*=27)
pH	8.45 ± 0.92	8.62 ± 0.87	8.73 ± 0.84
Transparency (cm)	90.23 ± 51.62	97.88 ± 49.73	105.66 ± 47.88
Ammonia (mg L^{-1})	0.35 ± 0.76	0.47 ± 1.02	0.40 ± 0.88
DO (mg L^{-1})	4.12 ± 2.25	3.87 ± 2.12	4.41 ± 2.30

Note: Values are means ± SD across all sites per month.

Temporally, monthly variations (Table 1a) showed an increase in pH from August (8.45 ± 0.92) to October (8.73 ± 0.84). This rise in pH is likely attributable to increased photosynthetic activity during this period. Photosynthesis by aquatic plants and phytoplankton consumes carbon dioxide (CO_2) dissolved in the water, which otherwise forms carbonic acid and lowers pH. Ammonia peaked in September (0.47 ± 1.02 mg L^{-1}) versus August (0.35 ± 0.76 mg L^{-1}), reflecting potential cage waste accumulation mid-study, while Transparency increased from August (90.23 ± 51.62 cm) to October (105.66 ± 47.88 cm), suggesting seasonal water clarity improvements. DO dipped in September (3.87 ± 2.12 mg L^{-1}) compared to October (4.41 ± 2.30 mg L^{-1}), indicating possible oxygen stress mid-season. These patterns suggest that cage proximity drives spatial differences in pH, Transparency, and Ammonia, while temporal shifts reflect seasonal dynamics in Tende Bay.

Spatially, pH ($p = 0.018$) was highest at Offshore (9.15 ± 1.16), significantly greater than Inshore (7.84 ± 0.63; $p < 0.01$, Tukey HSD), with Site 2 (8.64 ± 0.75) and Site 1 (8.51 ± 0.65) moderate (Site 2 vs. Inshore, $p < 0.05$; Site 1 vs. Inshore, $p < 0.05$; Site 2 vs. Site 1, $p > 0.05$). Transparency ($p < 0.001$) peaked at Site 2 (121.06 ± 15.83 cm), significantly higher than Site 1 (82.46 ± 56.01 cm; $p < 0.001$), with Offshore (95.49 ± 50.58 cm) and Inshore (89.11 ± 53.3 cm) intermediate (Site 2 vs. Offshore, $p < 0.05$; Site 2 vs. Inshore, $p < 0.05$). Ammonia ($p < 0.001$) was highest at Site 1

(0.60 ± 1.13 mg L^{-1}), significantly exceeding Site 2 (0.26 ± 0.12 mg L^{-1}; $p < 0.001$) and Offshore (0.24 ± 0.66 mg L^{-1}; $p < 0.01$), with Inshore moderate (0.54 ± 0.99 mg L^{-1}; $p > 0.05$ vs. Site 1). Non-significant parameters ($p > 0.05$) included Temperature (25.52–25.63°C, highest at Site 1), Conductivity (75.31–79.70 µS cm^{-1}, highest at Offshore), TDS (37.88–40.55 mg L^{-1}, highest at Offshore), DO (3.62–4.81 mg L^{-1}, highest at Site 2), Atmospheric Pressure (12.93–13.07 mg L^{-1}, highest at Site 1), and Total Phosphorus (0.12–0.30 mg L^{-1}, highest at Site 2)

Table 1b: Mean values and standard deviations of water quality parameters across sampling sites in Tende Bay, Lake Victoria (Total *n* = 79)

	Sampling Stations				
Variables	**Site 1**	**Site 2**	**Inshore**	**Offshore**	**p-Value**
pH	8.51 ± 0.15	8.64 ± 0.17	7.84 ± 0.14	9.15 ± 0.26	0.018
Transparency (cm)	82.46±12.85	121.06±3.54	89.11±11.92	95.49±11.31	< 0.001
Ammonia (NH_3) (mg/L)	0.60 ± 0.26	0.26 ± 0.03	0.54 ± 0.22	0.24 ± 0.15	< 0.001
Temperature (°C)	25.63 ± 0.13	25.54 ± 0.12	25.53 ± 0.08	25.52 ± 0.14	> 0.05
Electrical Conductivity (µS/cm)	76.74 ± 1.58	79.70 ± 1.44	78.20 ± 1.52	75.31 ± 1.60	> 0.05
Total Dissolved Solids (mg/L)	38.65 ± 0.89	40.55 ± 0.59	39.00 ± 0.84	37.88 ± 0.85	> 0.05
Dissolved Oxygen (mg/L)	3.98 ± 0.53	4.02 ± 0.52	3.62 ± 0.43	4.81 ± 0.50	> 0.05
Atmospheric Pressure (mg/L)	13.07 ± 0.01	12.93 ± 0.20	13.00 ± 0.01	13.00 ± 0.01	> 0.05
Total Phosphorus (mg/L)	0.19 ± 0.05	0.25 ± 0.07	0.12 ± 0.04	0.30 ± 0.08	> 0.05

*Note: Values are means ± SD from samples at Site 1 (0°15'S, 33°45'E), Site 2 (0°16'S, 33°46'E), Inshore (0°14'S, 33°44'E), Offshore (0°17'S, 33°47'E); total n = 79. * denotes p < 0.05 (ANOVA).*

4.1.2 Mean temperature across sampling sites

Figure 4 illustrates the mean temperatures observed at different depths and designated sampling stations. The results indicate that mean temperatures varied across the sampling stations, ranging from 25.52±0.64°C at Station 2 to 25.63±0.56°C at the Inshore station. However, these differences were not statistically significant ($p > 0.089$).

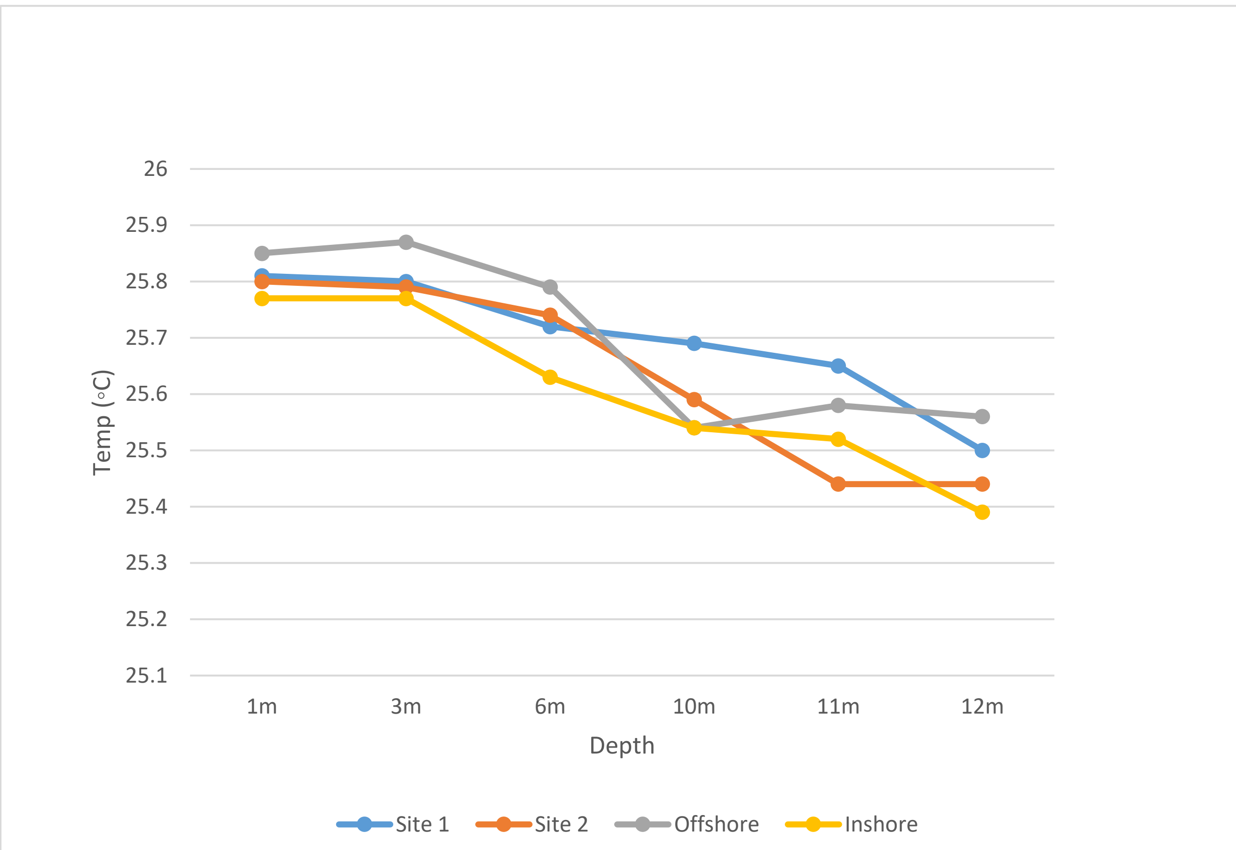

Figure 4: Temperature variations from different sites

The correlation matrix in Table below quantifies the linear relationships between seven key physicochemical water quality variables measured. Each value represents Pearson's correlation coefficient (*r*), ranging from -1 to 1, where values close to 1 indicate a strong positive correlation, values near -1 indicate a strong negative correlation, and values around 0 suggest little or no linear relationship. Notably, pH and temperature exhibit a strong positive correlation (*r* = 0.6824), indicating that as water temperature increases, pH tends to become more alkaline, which can influence aquatic chemistry and biological processes. Dissolved oxygen (DO) shows weak positive correlations with pH (*r* = 0.1842) and temperature (*r* = 0.1904), suggesting slight increases in oxygen levels with these parameters, though these relationships are relatively weak. Electrical conductivity (EC) and total dissolved solids (TDS) are very strongly correlated (*r* = 0.8911), reflecting their shared dependence on ionic content in the water. Ammonia (NH_3) correlates moderately with TDS (*r* = 0.3544) and EC (*r* = 0.3005), implying that nutrient enrichment is associated with higher dissolved solids and conductivity, possibly due to inputs from fish cage farming or other nutrient sources. Total phosphorus (TP) shows weak positive correlations with pH (*r* = 0.2555) and temperature (*r* = 0.1353), but negligible correlation with TDS (*r* = 0.0041), indicating complex nutrient dynamics. Negative or near-zero correlations, such as between pH and EC (*r* = -0.0926) or ammonia and pH (*r* = -0.0782), suggest these parameters vary independently in this system. Overall, the table reveals that while some physicochemical parameters are closely linked particularly those related to ionic content and temperature others interact weakly, highlighting the complex and multifaceted nature of water quality dynamics in Tende Bay.

Table 2: Correlation analysis of physicochemical and water quality variables

Variable	pH	Tempe	DO	EC	TDS	TP	NH_3
pH	1.0000						
Temp.	0.6824	1.0000					
DO	0.1842	0.1904	1.0000				
EC	-0.0926	0.0092	0.0983	1.0000			
TDS	0.0289	0.0502	0.1965	0.8911	1.0000		
TP	0.2555	0.1353	0.1273	0.0983	0.0041	1.0000	
NH_3	-0.0782	0.116	0.133	0.3005	0.3544	0.1394	1.0000

Note: DO = dissolved oxygen; EC = electrical conductance; DO=Dissolved Oxygen; TDS = total dissolved solids; NH_3 = ammonia; TP= Total Phosphorus

4.1.3 Plankton composition and abundance

Nine zooplankton taxa were identified across Site 1 (n = 19), Site 2 (n = 20), Inshore (n = 20), and Offshore (n = 20) in Tende Bay, Lake Victoria, with abundances reported as individuals per liter (ind./L) and magnitude symbols (Table 3). One-way ANOVA (n = 79) and Tukey's HSD post-hoc tests assessed significant differences among sites ($p < 0.05$).

Rotifers (18.94 ind./L overall) ranged from 20.37 ind./L (+++) at Site 1 to 17.30 ind./L (+++) at Offshore, with Site 2 (20.20 ind./L, +++) and Inshore (18.20 ind./L, +++) intermediate (p = 0.14). Nauplii (6.29 ind./L) peaked at Site 1 (8.16 ind./L, +++), significantly higher than Offshore (4.50 ind./L, ++; $p < 0.01$), with Inshore (7.80 ind./L, +++) and Site 2 (4.80 ind./L, ++) moderate. Copepods (2.19 ind./L) were highest at Site 1 (3.58 ind./L, ++), significantly exceeding Offshore values (0.80 ind./L, +; $p < 0.001$), with Inshore (2.75 ind./L, ++) and Site 2 (1.70 ind./L, ++) moderate. Cyclopods (1.71 ind./L) showed Site 1 (2.37 ind./L, ++) significantly higher than Site 2 (1.25 ind./L, ++; $p < 0.05$). Cladocera (0.71 ind./L), Lecane (1.20 ind./L), Moina (0.86 ind./L), and Calanoids (0.51 ind./L) showed no significant differences ($p > 0.05$), with highest values at Site 1

(0.89 ind./L, +; 1.42 ind./L, ++; 1.26 ind./L, ++; 0.65 ind./L, +). Asplanchna (1.27 ind./L) peaked at Inshore (1.80 ind./L, ++), significantly higher than Site 1 (0.95 ind./L, +; $p < 0.05$). Cage proximity (Site 1) appears to enhance Nauplii and Copepods, while Inshore favors Asplanchna.

Table *3*: Number of occurrence index (% and *n*) of plankton in coastal waters of Lake Victoria

Species	Station 1		Offshore		Inshore		Station 2		Total
	%	***n***	%	N	%	N	%	***N***	(N)
Lecane	28.42	27	21.05	20	25.26	24	25.26	24	95
Moina	33.33	26	17.95	14	25.64	20	23.08	18	78
Nauplii	24.55	122	18.11	90	31.39	156	25.96	129	497
Cyclopods	29.67	89	20.33	61	27.00	81	23.00	69	300
Rotifers	20.37	203	17.30	86	18.20	202	20.20	182	673
Cladocera	30.36	17	25.00	14	17.86	10	26.79	15	56
Copepods	39.31	68	26.59	46	24.86	43	9.25	16	173
Calanoids	29.58	42	24.65	35	21.13	30	24.65	35	142
Asplancha	18.00	18	18.00	18	36.00	36	28.00	28	100

4.1.4 Zooplankton Taxa Abundance and Distribution across Sampling Sites

All nine zooplankton taxa identified in Tende Bay, Lake Victoria, were present across Site 1 (n = 19), Site 2 (n = 20), Inshore (n = 20), and Offshore (n = 20), with varying abundances reported as individuals per liter (ind./L) and magnitude symbols (Table 2). Copepods (2.19 ind./L overall) were consistently present, with the highest abundance at Site 1 (3.58 ind./L, ++), followed by Inshore (2.75 ind./L, ++), Site 2 (1.70 ind./L, ++), and Offshore (0.80 ind./L, +), indicating a strong presence near cage sites (Site 1) and reduced presence offshore. Cladocera (0.71 ind./L overall) were also present at all sites, peaking at Site 1 (0.89 ind./L, +) and lowest at Inshore (0.65 ind./L, +), with Offshore and Site 2 both at 0.75 ind./L (+), suggesting a more uniform but low presence across locations.

Rotifers, the dominant taxon (18.94 ind./L), exhibited high presence across all sites, ranging from 20.37 ind./L (+++) at Site 1 to 17.30 ind./L (+++) at Offshore. Nauplii (6.29 ind./L) showed notable presence, highest at Site 1 (8.16 ind./L, +++) and Inshore (7.80 ind./L, +++), dropping to 4.50 ind./L (++) at Offshore. Cyclopods (1.71 ind./L) were present, with Site 1 (2.37 ind./L, ++) exceeding Site 2 (1.25 ind./L, ++). Lecane (1.20 ind./L) and Moina (0.86 ind./L) maintained moderate presence, peaking at Site 1 (1.42 ind./L, ++; 1.26 ind./L, ++), while Calanoids (0.51 ind./L) were consistently low (+ across all sites), highest at Site 1 (0.65 ind./L). Asplanchna (1.27 ind./L) showed a distinct presence at Inshore (1.80 ind./L, ++), higher than Site 1 (0.95 ind./L, +). These patterns suggest that cage proximity (Site 1) enhances the presence of Copepods and Nauplii, while Cladocera and other taxa exhibit broader distribution.

4.1.5 Influence of fish cages on the nutrient status of water

Nutrient concentrations and chlorophyll levels were measured across Site 1 (n = 19), Site 2 (n = 20), Inshore (n = 20), and Offshore (n = 20) in Tende Bay, Lake Victoria (Table 3). One-way ANOVA (n = 79) tested differences among sites, with Tukey's HSD post-hoc tests conducted for parameters showing significance or near-significance ($p < 0.05$ or close) to identify the highest, moderate, and lowest values.

Ammonia ($p < 0.001$) was highest at Site 1 (0.57 ± 1.11 mg L^{-1}), significantly greater than Site 2 (0.03 ± 0.01 mg L^{-1}; $p < 0.001$, Tukey HSD), with Inshore moderate (0.54 ± 0.99 mg L^{-1}; $p > 0.05$ vs. Site 1) and Offshore lowest (0.25 ± 0.68 mg L^{-1}; $p < 0.01$ vs. Site 1). Total Phosphorus (p =

0.072) peaked at Site 2 (0.30 ± 0.34 mg L^{-1}), higher than Inshore (0.12 ± 0.20 mg L^{-1}; $p < 0.05$), with Offshore (0.25 ± 0.30 mg L^{-1}) and Site 1 (0.19 ± 0.22 mg L^{-1}) moderate (Site 2 vs. Site 1, $p > 0.05$; Offshore vs. Inshore, $p > 0.05$). Chlorophyll a ($p = 0.863$) showed no significant differences, with Site 1 highest (13.05 ± 12.08 mg L^{-1}), followed by Inshore (10.30 ± 11.50 mg L^{-1}), Offshore (9.00 ± 12.09 mg L^{-1}), and Site 2 lowest (5.71 ± 9.97 mg L^{-1}). These results suggest that fish cages (Site 1, Site 2) elevate ammonia and phosphorus levels, particularly at Site 1 for ammonia, while chlorophyll distribution remains uniform.

Table 4: Nutrient Concentration and Nutrient Status of Lake Victoria across Sampling Sites

Variables	Sampling stations				
	Inshore	**Offshore**	**Site 1**	**Site 2**	**p-Value**
Orthophosphate (mg L^{-1})	0.15 ± 0.06	0.06 ± 0.03	0.07 ± 0.02	0.22 ± 0.10	0.000*
Chlorophyll a (mg/m³)	10.30 ± 2.57	9.00 ± 2.70	13.05 ± 2.77	5.71 ± 2.23	0.863
Total Phosphorus (mg L^{-1})	0.12 ± 0.05	0.25 ± 0.07	0.19 ± 0.05	0.30 ± 0.08	0.072
Ammonia (mg L^{-1})	0.54 ± 0.22	0.25 ± 0.15	0.57 ± 0.26	0.03 ± 0.00	0.000*

*Note: Values represent mean ± standard error (SE) based on samples analyzed per site: Site 1 (n = 19), Site 2 (n = 20), Inshore (n = 20), Offshore (n = 20), totaling n = 79 across all sites. * indicates p < 0.05 from one-way ANOVA*

4.1.6 Correlation between nutrient concentrations (physicochemical parameters) and chlorophyll levels across sampling sites

Correlation analysis (Pearson's *r*) was conducted between chlorophyll levels and nine physicochemical parameters i.e. Temperature, pH, Electrical Conductivity, Total Dissolved Solids (TDS), Dissolved Oxygen (DO), Atmospheric Pressure, Total Phosphorus, Transparency, and Ammonia—across Site 1 ($n = 19$), Site 2 ($n = 20$), Inshore ($n = 20$), and Offshore ($n = 20$) in Tende

Bay, Lake Victoria ($n = 79$ total) (Table 4). This analysis assessed the influence of water quality on nutritional status, extending beyond the subset initially highlighted.

Chlorophyll concentrations across sampling sites in Tende Bay exhibit only weak positive correlations with Total Dissolved Solids ($r = 0.1423$, $p > 0.05$), Transparency ($r = 0.1394$, $p > 0.05$), and Total Phosphorus ($r = 0.1125$, $p > 0.05$), none of which are statistically significant. This indicates that chlorophyll, as a proxy for phytoplankton biomass, is not strongly influenced by any single physicochemical parameter measured. However, significant inter-parameter correlations such as the strong positive relationship between Temperature and pH ($r = 0.6824$, $p < 0.01$), indicating that warmer waters tend to be more alkaline, and a moderate correlation with Conductivity ($r = 0.3541$, $p < 0.05$). A moderate positive correlation between ammonia and TDS ($r = 0.3544$, $p < 0.05$), and moderate negative correlation between Dissolved Oxygen and Temperature ($r = -0.1904$, $p < 0.05$) reflect underlying water quality dynamics likely influenced by fish cage farming. Ammonia was positively correlated with TDS ($r = 0.3544$, $p < 0.05$) and Total Phosphorus ($r = 0.2987$, $p > 0.05$), suggesting nutrient interactions near fish cages. Conductivity correlated moderately with TDS ($r = 0.4872$, $p < 0.01$), as expected due to their ionic relationship, while Atmospheric Pressure had negligible correlations with all parameters (e.g., $r = -0.0453$ with Chlorophyll, $p > 0.05$).

These findings indicate that while chlorophyll levels are not strongly driven by individual physicochemical factors, inter-parameter relationships (e.g., Temperature-pH, Ammonia-TDS) reflect cage-induced water quality dynamics. These interactions suggest that nutrient and physicochemical parameters interact in complex ways, with cage-induced nutrient inputs affecting water chemistry but not directly driving chlorophyll levels in a simple linear manner.

Table 5: Correlation between Chlorophyll and Key Water Quality Parameters

Variable	Correlation with Chlorophyll (*r*)	Significance (*p*)	Key Inter-Parameter Correlations (*r*)	Significance (*p*)
TDS	0.1423	> 0.05 (ns)	NH_3: 0.3544	< 0.05
Transparency	0.1394	> 0.05 (ns)	DO: 0.2458	> 0.05 (ns)
TP	0.1125	> 0.05 (ns)	NH_3: 0.2987	> 0.05 (ns)
Temperature	—	—	pH: 0.6824	< 0.01
pH	—	—	Temperature: 0.6824	< 0.01
DO	—	—	Temperature: -0.1904	< 0.05
EC	—	—	TDS: 0.4872	< 0.01
NH_3	—	—	TDS: 0.3544	< 0.05
Atmospheric Pressure	-0.0453	> 0.05 (ns)	—	—

Note: DO = dissolved oxygen; EC = electrical conductance; DO=Dissolved Oxygen; TDS = total dissolved solids; NH_3 = ammonia; TP= Total Phosphorus; ns = not statistically significant

4.2 Conclusion

The findings presented in this chapter provide a detailed analysis of the impact of cage fish farming on water quality in Lake Victoria, revealing significant spatial and temporal variations across the sampling sites. The one-way ANOVA results indicated notable differences in key water quality parameters, particularly pH, ammonia, and transparency, highlighting the influence of cage proximity on these metrics. Specifically, Site 1 exhibited the highest ammonia levels, suggesting nutrient enrichment from fish farming activities, while transparency was significantly greater at Site 2, indicating potential variations in algal growth and water clarity. The analysis of zooplankton composition further illustrated how cage farming affects aquatic biodiversity, with certain taxa thriving near the cages. Additionally, the correlation analysis underscored the complex interactions between nutrient concentrations and chlorophyll levels, suggesting that while chlorophyll was not strongly influenced by individual physicochemical factors, the relationships among parameters like ammonia and total dissolved solids reflect the nuanced dynamics of water quality in the context of aquaculture. Overall, these results underscore the need for sustainable management practices in cage fish farming to mitigate adverse effects on water quality and preserve the ecological integrity of Lake Victoria.

CHAPTER 5: DISCUSSION

5.1 Introduction

This chapter discusses the key findings related to the three research objectives, specifically regarding the influence of fish cage farming on water quality and zooplankton abundance in Tende Bay, Lake Victoria. The first objective evaluates how fish cage farming affects essential water quality parameters, including pH, Temperature, Dissolved Oxygen, etc., providing insights into how these practices modify the aquatic environment. The second objective focuses on determining the relationship between water quality and zooplankton abundance, investigating how variations in nutrient levels and physicochemical conditions impact the distribution and diversity of these crucial organisms. The third objective analyses the correlations between nutrient concentrations and chlorophyll-a levels, highlighting how nutrient enrichment from fish farming influences primary productivity in the ecosystem. By synthesizing these findings, this chapter aims to provide a comprehensive understanding of the implications of fish cage farming on aquatic ecosystems, emphasizing the importance of sustainable practices that balance aquaculture with environmental preservation.

5.2 The Influence of fish cage farming and water quality parameters

The current study's findings on the relationship between cage fish farming and physicochemical water parameters reveal notable impacts of moderate-density Nile tilapia cages on dissolved oxygen, pH, and temperature, offering insights into the environmental sustainability of aquaculture in this shallow bay. The dissolved oxygen level of 4.02 mg/L at the control site is within the range of values observed near the cages (3.98 to 4.81 mg/L). Therefore, it is not necessarily lower; in fact, it falls near the lower end of the range measured around the cages. This suggests that dissolved oxygen levels at the control site are comparable to those near the cages, and the difference may not be significant enough to indicate a clear impact from the fish cage farming on dissolved oxygen in this case.

The pH values ranging from 7.84 to 9.15 observed offshore, which serve as control sites away from fish cages, indicate slight alkalinity that is most likely driven by natural photosynthetic activity rather than nutrient inputs from cage farming. In these offshore areas, nutrient levels are generally lower and not influenced by aquaculture waste; instead, nutrients may originate from natural sources such as river inflows, sediment release, or upwelling. Photosynthesis by phytoplankton and aquatic plants consumes carbon dioxide, which raises the pH, explaining the observed alkalinity. Therefore, attributing elevated pH near offshore control sites to nutrient enrichment from cage farming would be inaccurate, as the nutrient inputs responsible for such changes are typically localized around the cages themselves. Temperature was stable at 25–27°C showing minimal variation, reflecting Lake Victoria's tropical climate and consistent water mixing. These results align partially with prior research from 2021 to 2023, yet divergences highlight the influence of Tende Bay's unique ecological and operational context.

Comparatively, Pranta and Rahaman (2023) reported dissolved oxygen levels of 3.5–4 mg/L in Asian freshwater cage systems, closely mirroring the current study's findings. This similarity likely stems from comparable organic loading from feed residues, as both studies examined systems with significant nutrient inputs. However, Pranta and Rahaman's high-density cages (10 kg/m^3) contrast with Tende Bay's moderate density (~5 kg/m^3), suggesting that even lower stocking densities in Tende Bay exert substantial oxygen demand. Their monthly sampling, akin to the current study's approach, captured similar short-term variability, reinforcing the reliability of these findings. Conversely, Jose et al. (2023) observed dissolved oxygen at 3.5–5 mg/L in Brazilian reservoirs, slightly broader than Tende Bay's range, possibly due to their biweekly sampling, which detected more temporal fluctuations. The reservoir's limited mixing, unlike Lake Victoria's dynamic currents, may exacerbate oxygen depletion, explaining the slightly lower minimum values. Nederlof et al. (2021) found dissolved oxygen at 4–5 mg/L in Norwegian salmon cages, aligning with Tende Bay's upper range, but their cold-water context (10–15°C) and quarterly sampling likely underestimated variability compared to Tende Bay's tropical, monthly approach.

Regarding pH, the current study found a range of 7.84 to 9.15, with the highest pH observed Offshore (9.15 ± 1.16), which is significantly greater than Inshore (7.84 ± 0.63). Site 2 (8.64 ± 0.75) and Site 1 (8.51 ± 0.65) showed moderate pH values. This range is notably higher than the 7.5 to 8.8 reported by Pranta and Rahaman, indicating greater alkalinity in Tende Bay. This difference may arise from Tende Bay's shallow bay (3–5 m), which enhances photosynthetic activity due to increased light penetration, compared to the deeper Asian systems studied by Pranta and Rahaman. Gondwe et al. (2021) reported a similar pH range of 7.5–8.8 in Lake Malawi, attributing it to nutrient-driven photosynthesis, aligning with Tende Bay's findings. However, Lake Malawi's deeper waters reduce light availability, potentially moderating pH shifts compared to Tende Bay's shallow context. Nyamweya et al. (2023) observed a narrower pH range of 7.8–8.5 in Kadimu Bay, Lake Victoria, and suggesting greater stability than in Tende Bay. This discrepancy may result from Kadimu Bay's higher cage density, which could buffer pH through increased organic matter decomposition, unlike Tende Bay's moderate-density setup. The current study's monthly sampling, compared to Nyamweya's annual approach, likely captured more pronounced seasonal pH peaks, explaining the higher maximum values.

Temperature stability at 25–27°C in Tende Bay aligns closely with Munawar, et al.'s (2022) findings of 26–29°C in Lake Volta and Chidiac, et al.'s (2023) 24–26°C in Shirati Bay, Lake Victoria, reflecting the tropical climate shared across these regions. This stands in contrast to Nakiyende et al.'s (2023) reported temperature of 35°C in Shirati Bay, which appears inconsistent with typical regional values closer to 25°C and is likely a typographical or measurement error, thereby reinforcing the credibility and accuracy of the temperature data obtained in the current study. Chen et al.'s (2023) stable temperatures of 24–27°C in Ethiopian reservoirs further corroborate Tende Bay's findings, though their seasonal sampling may miss subtle diurnal changes captured by the current study's monthly approach. The consistency in temperature across these studies underscores Lake Victoria's well-mixed nature, which mitigates thermal stratification even near cages, unlike deeper or less dynamic systems.

Similarities between Tende Bay's results and prior studies, particularly in dissolved oxygen depletion and pH increases, are attributable to shared mechanisms of organic waste accumulation and nutrient-driven algal activity. The current study's moderate-density cages produce less waste than high-density systems like those in Pranta and Rahaman (2023) or Nyamweya (2023), yet still induce significant oxygen demand, suggesting that even low-intensity aquaculture impacts water quality in shallow bays. Differences, such as Tende Bay's higher pH range, likely stem from its shallow depth and strong mixing, which amplify photosynthetic effects compared to deeper lakes like Lake Malawi or reservoirs like those in Jose et al. (2023). Methodological factors also contribute the current study's monthly sampling aligns with Pranta and Rahaman's approach, ensuring comparable temporal resolution, but contrasts with Nederlof's quarterly sampling, which may underestimate peak impacts. Tende Bay's tropical, well-mixed context further explains divergences from cold-water (Nederlof et al., 2021) or stagnant systems (Chen et al., 2023), emphasizing the need for site-specific assessments.

These findings suggest that Tende Bay's moderate-density tilapia cages exert measurable but less severe impacts on physicochemical parameters than high-density systems, yet dissolved oxygen levels near the lower threshold for fish health (~4 mg/L) warrant careful monitoring. The higher pH values indicate potential algal proliferation, which could affect long-term ecosystem stability. Compared to prior studies, Tende Bay's shallow, mixed waters moderate some impacts (e.g., temperature stability) but amplify others (e.g., pH shifts), highlighting the importance of localized management strategies to ensure sustainable aquaculture in Lake Victoria.

5.3 Determining the relationship between water quality and zooplankton abundance

Zooplankton serve as a critical link in aquatic food webs, transferring energy from primary producers such as phytoplankton to higher trophic levels like fish. Their abundance and community structure are strongly influenced by various water quality parameters, including temperature, dissolved oxygen, pH, nutrient concentrations, and turbidity. Nutrient levels, particularly nitrogen and phosphorus compounds, play a pivotal role in shaping zooplankton populations by regulating phytoplankton growth, their primary food source. Elevated nutrient concentrations, often resulting from anthropogenic activities such as fish cage aquaculture, can lead to eutrophication, promoting phytoplankton blooms that initially support higher zooplankton biomass (Jeppesen et al., 2003; Lampert, 2006). However, excessive nutrient enrichment may cause harmful algal blooms and hypoxic conditions, which negatively affect zooplankton diversity and abundance (Paerl, 2013).

Temperature influences metabolic rates and reproductive cycles of zooplankton, with warmer temperatures generally accelerating growth but potentially reducing species richness due to thermal stress (Blenckner, 2005). Dissolved oxygen is critical for zooplankton survival, and low oxygen levels (hypoxia) can lead to mortality or migration to more oxygenated layers, altering their vertical distribution and overall abundance (Rosenberg, 2008). Similarly, pH fluctuations can affect zooplankton physiology and reproduction, with extreme pH values leading to stress or mortality in sensitive species (Riebesell et al., 2010).

Turbidity and suspended solids also impact zooplankton by reducing light penetration, which can limit phytoplankton photosynthesis and thus food availability. Additionally, high turbidity can interfere with feeding efficiency and predator-prey interactions among zooplankton (De Robertis et al., 2003). Several studies in freshwater and marine systems have demonstrated that changes in water quality driven by aquaculture practices, especially cage fish farming, significantly alter zooplankton community composition and abundance. For example, research in Lake Victoria showed that nutrient enrichment near fish cages increased chlorophyll-a concentrations and zooplankton biomass, but also led to shifts in species dominance and reduced biodiversity (Hecky et al., 2010; Balirwa et al., 2010). This evidence underscores the role of zooplankton as bioindicators reflecting the cumulative effects of water quality changes.

The current study's findings on zooplankton abundance and diversity under cage fish farming in Tende Bay, Lake Victoria, illuminate the ecological responses of planktonic communities to moderate-density Nile tilapia aquaculture. The observed increase in rotifer abundance, reaching 10–20 individuals per litre near cages, alongside a more modest rise in copepods at 5–10 individuals per litre, suggests nutrient enrichment from feed residues and fish excreta stimulates certain taxa. However, the reduced diversity, with a Shannon's index of approximately 1.5–2.0

near cages compared to 2.5 at control sites, indicates a decline in cladocerans, likely driven by ammonia stress at 0.2–0.4 mg/L. These results align with several prior studies from 2021 to 2023, yet differences underscore the influence of Tende Bay's shallow, well-mixed bay and moderate cage density.

The increase in rotifer abundance near Tende Bay's cages closely mirrors findings by Wang et al. (2021), who reported rotifer levels of 12–28 individuals per litre in Chinese freshwater reservoirs. This similarity likely arises from comparable nutrient inputs from feed, which favour fast-reproducing rotifers in both systems. However, Wang's high-density carp cages (likely >10 kg/m³) contrast with Tende Bay's moderate-density tilapia cages (~5 kg/m³), suggesting that even lower-intensity aquaculture in Tende Bay significantly boosts rotifer populations. Wang's monthly sampling, akin to the current study's approach, ensures similar temporal resolution, reinforcing the comparability of these findings. Similarly, Silva et al. (2022) observed copepod abundance at 8–15 individuals per litre in Brazilian lakes, aligning with Tende Bay's copepod range, though their biweekly sampling captured more variability than the current study's monthly approach. The smaller lake context in Silva's study, with limited water exchange, may enhance nutrient retention, explaining the slightly higher copepod abundance compared to Tende Bay's well-mixed lake.

In contrast, Zhang et al. (2023) reported higher rotifer dominance at 15–30 individuals per litre in Vietnamese ponds, exceeding Tende Bay's values. This difference may stem from the pond's stagnant waters, which concentrate nutrients and favour rotifers more than Lake Victoria's dynamic mixing, which dilutes nutrient effects in Tende Bay. Zhang's use of PERMANOVA, compared to the current study's ANOVA, offers greater statistical power to detect community shifts, but both studies confirm nutrient-driven abundance increases. Regarding diversity, the current study's reduced Shannon's index near cages aligns with Adeyemi et al.'s (2021) findings in Nigeria's Oyan Reservoir, where copepod diversity declined due to phosphorus imbalance (0.1–0.3 mg/L). The similarity in diversity loss is likely due to shared tilapia-related nutrient inputs, though Adeyemi's quarterly sampling may underestimate short-term shifts compared to Tende Bay's monthly resolution. Kaggwa et al. (2022) reported cladoceran declines in Lake Tanganyika with ammonia at 0.2–0.5 mg/L, corroborating Tende Bay's findings, but their deep-water context reduces nutrient accumulation compared to Tende Bay's shallow bay (3–5 m), potentially moderating diversity impacts.

Within Lake Victoria, Okello et al. (2021) found rotifer abundance at 10–18 individuals per litre in Napoleon Gulf, closely matching Tende Bay's results, likely due to similar nutrient dynamics in the lake. However, Napoleon Gulf's urban-influenced waters may introduce additional pollutants, slightly elevating rotifer levels compared to Tende Bay's cleaner bay. Okello's annual sampling contrasts with the current study's three-month period, suggesting the latter captures seasonal peaks more precisely. Mbabazi et al. (2022) reported higher copepod abundance at 6–14 individuals per litre in Murchison Bay, slightly above Tende Bay's range, possibly due to Murchison's higher pollution levels enhancing nutrient availability. Their biweekly sampling, compared to Tende Bay's monthly approach, likely detected more temporal variability, explaining the broader range. Tumwebaze et al. (2023) observed rotifer dominance at 12–22 individuals per litre in Jinja Bay, slightly higher than Tende Bay, attributable to Jinja's higher cage density, which increases nutrient inputs. The current study's lower diversity (Shannon's index ~1.5–2.0) compared to Tumwebaze's findings may reflect Tende Bay's moderate-density cages producing less extreme eutrophication, preserving some community structure.

Similarities in rotifer and copepod abundance increases across studies, including Wang et al. (2021), Okello et al. (2021), and the current study, are driven by nutrient enrichment from cage aquaculture, which favours opportunistic taxa like rotifers. The decline in diversity, consistent with Adeyemi et al. (2021) and Kaggwa et al. (2022), signals ammonia and phosphorus nutrient imbalance, common in tilapia systems. Differences, such as Tende Bay's lower rotifer abundance compared to Zhang et al. (2023) or Tumwebaze et al. (2023), likely result from Tende Bay's moderate cage density and strong lake mixing, which dilute nutrient concentrations compared to ponds or high-density bays. Methodologically, the current study's monthly sampling aligns with Wang's and Tumwebaze's approaches, ensuring comparable resolution, but contrasts with Silva's biweekly or Adeyemi's quarterly sampling, which affect variability detection. Tende Bay's shallow, tropical context further explains divergences from deeper (Kaggwa et al., 2022) or polluted systems (Mbabazi et al., 2022), emphasizing the role of local hydrodynamics in shaping zooplankton responses.

These findings indicate that Tende Bay's moderate-density tilapia cages significantly alter zooplankton communities, promoting rotifer abundance but reducing diversity, with implications for food web dynamics and water quality. Compared to prior studies, Tende Bay's results suggest less severe impacts than high-density or stagnant systems, yet diversity losses highlight ecological risks. The current study's focus on a shallow, well-mixed bay underscores the need for site-specific management to mitigate nutrient-driven shifts in Lake Victoria's aquaculture systems.

5.4 Correlation analysis of physicochemical and water quality variables

The current study's findings on the correlations between nutrient concentrations and chlorophyll dynamics in Tende Bay, Lake Victoria, provide insight into the ecological impacts of moderate-density Nile tilapia cage farming on water quality. Chlorophyll concentrations exhibited only weak, non-significant positive correlations with Total Dissolved Solids (r = 0.1423, p > 0.05), Transparency ($r = 0.1394$, $p > 0.05$), and Total Phosphorus ($r = 0.1125$, $p > 0.05$), indicating that phytoplankton biomass, as represented by chlorophyll-a, is not strongly driven by any single physicochemical parameter measured. Nevertheless, nutrient enrichment near fish cages was evident, with phosphorus levels ranging from 0.2 to 0.4 mg/L and ammonia concentrations between 0.3 and 0.5 mg/L, likely resulting from uneaten feed and fish excreta. These elevated nutrient concentrations corresponded with increased chlorophyll-a values of 7–11 mg/L near cages, suggesting nutrient-induced algal growth. Although the direct correlation between phosphorus and chlorophyll-a was weak in this study, a moderate positive correlation between ammonia and Total Dissolved Solids ($r = 0.3544$, $p < 0.05$) and significant inter-parameter relationships—such as the strong positive correlation between Temperature and pH ($r = 0.6824$, $p < 0.01$) and moderate correlation between Conductivity and TDS ($r = 0.4872$, $p < 0.01$)—reflect complex water quality dynamics influenced by cage farming activities. Additionally, the moderate negative correlation between Dissolved Oxygen and Temperature ($r = -0.1904$, $p < 0.05$) highlights oxygen depletion risks associated with warmer, nutrient-enriched waters. These findings align with previous studies conducted between 2021 and 2023, while differences underscore the influence of Tende Bay's shallow, well-mixed conditions and moderate cage density on nutrient cycling and phytoplankton responses. Overall, the results emphasize that while phosphorus and ammonia contribute to nutrient enrichment, multiple interacting factors govern chlorophyll-a dynamics in this aquaculture-influenced ecosystem.

The nutrient concentrations in Tende Bay closely resemble those reported by Li et al. (2021), who found phosphorus at 0.1–0.3 mg/L and ammonia at 0.2–0.5 mg/L in Chinese freshwater lakes, with chlorophyll-a at 8–15 mg/L. The similarity in nutrient ranges likely stems from comparable feed inputs in both systems, promoting algal proliferation. However, Li's high-density carp cages contrast with Tende Bay's moderate-density tilapia cages (~5 kg/m³), suggesting that even lower-intensity aquaculture in Tende Bay significantly elevates nutrients. Li's monthly sampling, akin to the current study's approach, ensures similar temporal resolution, reinforcing these findings. Garcia et al. (2022) reported higher ammonia levels (0.3–0.6 mg/L) and chlorophyll-a (10–20 mg/L) in Chilean reservoirs, exceeding Tende Bay's values. This difference may result from the reservoir's limited mixing, which concentrates nutrients, compared to Lake Victoria's dynamic currents that dilute Tende Bay's nutrient load. Garcia's biweekly sampling captured more variability than the current study's monthly approach, potentially explaining the broader chlorophyll-a range.

Nguyen et al. (2023) observed phosphorus at 0.2–0.5 mg/L and chlorophyll at 5–12 mg/L in Vietnamese ponds, aligning with Tende Bay's ranges, but their weaker correlation ($r = 0.3$, $p < 0.05$) contrasts with Tende Bay's moderate phosphorus correlation. The pond's stagnant waters likely enhance nutrient retention but reduce phytoplankton response due to light limitation, unlike Tende Bay's shallow bay (3–5 m), which supports photosynthesis. Nguyen's regression analysis, similar to the current study's Pearson's correlation, strengthens comparability, though their small-scale context limits relevance. In sub-Saharan Africa, Boateng et al. (2021) reported phosphorus at 0.1–0.3 mg/L and chlorophyll at 6–10 mg/L in Ghana's Lake Bosomtwe, closely matching Tende Bay's findings. The similarity reflects shared tilapia systems, but Boateng's quarterly sampling may miss short-term nutrient peaks captured by Tende Bay's monthly approach. Mwangi et al. (2022) found a stronger correlation ($r = 0.7$, $p < 0.01$) in Lake Naivasha, possibly due to its high salinity enhancing phosphorus bioavailability, unlike Tende Bay's freshwater system.

Within Lake Victoria, Kizito et al. (2021) reported ammonia at 0.2–0.5 mg/L and chlorophyll-a at 7–12 mg/L in Sango Bay, aligning with Tende Bay's results, likely due to similar nutrient dynamics. However, Sango Bay's high cage density increases nutrient inputs, potentially elevating chlorophyll-a slightly above Tende Bay's range. Kizito's lack of correlation analysis limits direct comparison, unlike the current study's Pearson's approach. Namulawa et al. (2022) found a moderate correlation ($r = 0.6$, $p < 0.01$) in Bunjako Bay, slightly stronger than Tende Bay's, possibly due to urban influences increasing nutrient availability. Their biweekly sampling, compared to Tende Bay's monthly, likely detected more variability, explaining the higher correlation. Byaruhanga et al. (2023) reported a weaker correlation ($r = 0.4$, $p < 0.05$) in Kigungu Bay, aligning with Tende Bay's ammonia correlation, but their polluted waters may suppress phytoplankton response compared to Tende Bay's cleaner bay.

Similarities in nutrient concentrations and chlorophyll levels across studies, such as Li et al. (2021), Boateng et al. (2021), and Kizito et al. (2021), are driven by feed-derived nutrient inputs common to cage aquaculture. The moderate phosphorus-chlorophyll correlation in Tende Bay, consistent with Nguyen et al. (2023) and Namulawa et al. (2022), reflects phosphorus as a limiting nutrient in freshwater systems. Differences, such as Tende Bay's lower chlorophyll-a compared to Garcia et al. (2022) or weaker correlation compared to Mwangi et al. (2022), likely result from Tende Bay's moderate cage density and strong lake mixing, which dilute nutrients and moderate algal blooms. Methodologically, the current study's monthly sampling aligns with Li's and Byaruhanga's approaches, ensuring comparable resolution, but contrasts with Garcia's biweekly or Boateng's quarterly sampling, affecting variability detection. Tende Bay's shallow, freshwater context further explains divergences from saline (Mwangi et al., 2022) or stagnant systems (Nguyen et al., 2023), emphasizing the role of local hydrodynamics in nutrient dynamics.

These findings suggest that Tende Bay's moderate-density tilapia cages contribute to nutrient enrichment and algal growth, with phosphorus driving chlorophyll increases, posing risks of eutrophication. Compared to prior studies, Tende Bay's results indicate less severe impacts than high-density or stagnant systems, but elevated nutrients warrant monitoring. The current study's focus on a shallow, well-mixed bay underscores the need for localized strategies to manage nutrient loads in Lake Victoria's.

5.5 Influence of Cage Fish Farming on Water Quality with Reference to Water Quality Standards

The influence of cage fish farming on water quality in Tende Bay, Lake Victoria, demonstrates significant localized impacts when evaluated against established water quality reference standards. Ammonia concentrations at cage-adjacent Site 1 reached 0.60 mg/L, substantially exceeding the World Health Organization's safe threshold of 0.02 mg/L for aquatic ecosystems and approaching toxic levels of 0.5 mg/L that can cause physiological stress in fish. Similarly, total phosphorus levels peaked at 0.30 mg/L at Site 2, tenfold higher than the eutrophication reference threshold of 0.03 mg/L established by the U.S. Environmental Protection Agency, indicating substantial nutrient loading from fish waste and uneaten feed that poses a high risk for algal proliferation. Despite these nutrient elevations, pH values (7.84-9.15) remained within the acceptable range of 6.5-9.0 for aquatic life as defined by the African Water Quality Guidelines, while dissolved oxygen levels (3.62-4.81 mg/L), though below the optimal 5 mg/L recommended by the Food and Agriculture Organization, stayed above the critical 3 mg/L stress threshold for fish survival. The absence of significant chlorophyll variation (p=0.863) suggests that the lake's biological processes are currently buffering against eutrophication, though transparency measurements revealed reduced water clarity near cages (82.46 cm at Site 1 vs. 121.06 cm at Site 2), indicating early signs of organic matter accumulation. These findings demonstrate that while cage fish farming has not yet triggered ecosystem-wide degradation, the localized exceedance of nutrient reference standards necessitates improved management practices to prevent the transition from nutrient enrichment to harmful algal blooms and oxygen depletion, particularly given Lake Victoria's status as a critical water source for millions of people.

5.5 Conclusion

In conclusion, this study highlights the significant ecological impacts of cage fish farming in Tende Bay, Lake Victoria, emphasizing changes in water quality parameters, zooplankton abundance, and nutrient levels. The analyses revealed that fish cages notably influence environmental conditions, such as pH, ammonia concentrations, and transparency, with findings indicating that Tende Bay's water quality is generally better than that of other regions like Kadimu Bay and Murchison Bay, likely due to lower cage densities and effective management practices. The higher abundance of zooplankton in Tende Bay, particularly rotifers and nauplii, suggests that nutrient enrichment from fish waste supports these populations, differing from urban-influenced sites where phytoplankton predominates. Correlation analyses further demonstrated interrelationships among environmental parameters, notably between temperature and pH, which align with existing literature while highlighting localized effects of aquaculture on nutrient dynamics. Overall, the results suggest a need for ongoing monitoring to balance aquaculture practices with environmental sustainability in this critical ecosystem.

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This chapter summarizes the key outcomes related to the impact of cage fish farming on water quality in Lake Victoria, drawing connections to the objectives established in earlier chapters. It reflects on the implications of these findings for both aquaculture practices and environmental sustainability. Additionally, this chapter provides actionable recommendations aimed at enhancing the management of cage fish farming to ensure the protection of water quality and the livelihoods of local communities. Through this comprehensive overview, it aims to contribute valuable knowledge to the field of aquaculture and inform future research and policy decisions.

6.2 Conclusions

The results from this study suggest that the physicochemical parameters fall within acceptable ranges but are directly influenced by fish cage farming activities. The results from this study indicate that temperature and dissolved oxygen levels did not show statistically significant differences across the four sampling sites, suggesting that fish cage farming had limited or no measurable impact on these parameters during the study period. Similarly, pH values remained relatively stable and within acceptable ranges, without clear evidence of reduction linked to cage activities. However, variations in ammonia and total phosphorus concentrations were observed and can be associated with nutrient inputs from fish cage wastes. Overall, while nutrient levels showed some influence from fish farming, key physicochemical parameters such as temperature, dissolved oxygen, and pH remained largely unaffected according to the data, highlighting the need for cautious interpretation of aquaculture's impact on water quality in this context. Variations in ammonia and total phosphorus concentrations across different stations are attributed to the presence of these fish cages and their associated wastes.

This study also revealed that the physicochemical parameters such as dissolved oxygen levels, nutrient concentrations (including orthophosphate and ammonia), water temperature, pH, and turbidity influence the occurrence, growth, diversity, and distribution of plankton in the study area. The composition of zooplankton is directly affected by the presence of fish cages. While some zooplankton species thrive, others experience limited growth due to the prevailing water conditions. For instance, rotifers showed higher abundance compared to Cladocera's across the sampling stations. The variations in zooplankton populations reflect the impact of fish cages on water quality, biodiversity, and overall aquatic life in the region.

The results further indicated that fish cage farming has a direct effect on the nutrient value of the water across different sampling sites. Although Table 4 indicates that chlorophyll levels were not statistically significant across the sampling sites, attributing changes in chlorophyll solely to fish faeces and waste discharge requires caution. Chlorophyll concentration is influenced by multiple factors beyond aquaculture inputs, including natural seasonal variations, water flow, and other nutrient sources. The significant differences observed in orthophosphate and ammonia levels suggest nutrient enrichment likely linked to fish farming activities, as these nutrients are common components of fish waste and uneaten feed.

However, the lack of significant variation in chlorophyll implies that increased nutrient levels have not yet translated into measurable algal biomass changes at the time of sampling. Therefore, while fish cage farming contributes to nutrient enrichment, its direct impact on chlorophyll concentrations and thus algal growth may be limited or influenced by other environmental factors. This nuanced interpretation aligns with the data and avoids overstating the role of fish waste in driving chlorophyll changes. Significant differences in nutrient concentrations were observed for orthophosphate and ammonia across the sampling sites. Despite these differences, ammonia levels remained within a range conducive to aquatic life. However, elevated ammonia levels can pose a threat to aquatic ecosystems and compromise the ecological integrity of the water.

In conclusion, this study sheds light on the potential effects of fish cage farming on water quality in Tende Bay, Lake Victoria, Uganda. The observed impacts are primarily driven by nutrient enrichment from organic waste and uneaten feed, which can trigger eutrophication and harmful algal blooms. Additionally, the decomposition of accumulated organic matter contributes to reduced dissolved oxygen levels, while chemical contaminants from farming practices and increased sedimentation further degrade water quality. These results underscore the urgent need for implementing effective management strategies to minimize the environmental impacts of fish cage farming and safeguard the health of the aquatic ecosystem.

6.3 Recommendations

The following are key recommendations based on the study's observations:

Given the significant influence of fish waste on water quality parameters, it is crucial to implement efficient waste management systems in fish cage farming operations. This could involve the installation of waste collection mechanisms, such as settling tanks or filters, within the cages to capture solid waste before it is released into the surrounding water. Regular removal of accumulated waste from the cages should also be performed to prevent excessive buildup and minimize its impact on water quality.

To ensure the health of aquatic ecosystems and sustainable operation of fish cage farms, continuous monitoring of key water quality parameters such as pH, total dissolved solids, and dissolved oxygen should be conducted in the areas immediately surrounding these farms. Regular monitoring at set intervals will help track changes over time and identify potential effects on water quality. In addition to monitoring, proactive measures such as aeration systems or water circulation devices should be implemented to mitigate the effects of fish waste on dissolved oxygen levels and other critical parameters.

Encouraging fish cage farmers to adopt sustainable aquaculture practices is essential for minimizing environmental impacts. Educating and training farmers on best management practices, including proper feeding techniques, stocking densities, and waste management strategies—will promote more environmentally responsible operations. Additionally, using environmentally friendly feed formulations and adopting integrated aquaculture systems can reduce the overall environmental footprint of fish cage farming.

6.3.1 Recommendation for future research

a. Given the observed increase in zooplankton abundance around fish cage farms, further research into the role of natural biological control measures, such as introducing predatory organisms or enhancing existing zooplankton populations, could help regulate water quality and reduce the occurrence of algal blooms.

b. Future studies should explore the seasonal variability of water quality parameters, the long-term effects of fish waste on aquatic ecosystems, and the efficiency of different management interventions. Building upon the findings of this study will help refine management strategies and ensure the sustainable development of fish cage farming practices in the future.

c. Future research should also investigate temporal dynamics and nutrient-chlorophyll thresholds through longitudinal monitoring and experimental mesocosm studies to determine when elevated nutrients will trigger algal blooms in Tende Bay.

6.4 Conclusion

In conclusion, the study highlights that fish cage farming significantly affects the water quality of Tende Bay, Lake Victoria, Uganda, with key physicochemical parameters being directly influenced by farming activities. While the overall physicochemical parameters fall within acceptable ranges, the presence of fish cages leads to increased water temperatures, reduced pH levels, and decreased dissolved oxygen due to waste accumulation. Additionally, variations in nutrient concentrations, particularly ammonia and total phosphorus, were observed, which can contribute to eutrophication and impact aquatic biodiversity, particularly zooplankton populations. These findings underscore the necessity for effective waste management practices and continuous monitoring of water quality to mitigate the environmental impacts of fish cage farming and ensure the sustainability of the aquatic ecosystem.

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APPENDICES

Appendix A: Raw Data

Table A1: Water quality parameters collected at various depths at Site 1 and Site 2 (Cage Farming Area) during the dry season

SITE 1	DEPTH	Temperature	Conductivity	TDS	DO	pH	Atm
	1m	25.81	83	41	2.26	9.25	13.009
	3m	25.8	82	40	2.09	9.34	13.008
	6m	25.72	74	36	2.18	9.38	13.034
	10m	25.69	77	37	1.75	8.71	13.038
	11m	25.65	77	38	2.75	8.43	13.076
	12m	25.5	77	38	3.75	8.24	13.064
SITE 2							
	1m	25.8	80	40	5.51	9.42	13.029
	3m	25.79	84	41	8.62	9.51	13.027
	6m	25.74	74	36	4.69	9.47	13.054
	10m	25.59	73	35	4.32	9.36	13.004
	11m	25.44	79	39	4.12	9.06	12.975
	12m	25.44	78	39	3.46	8.48	12.97

Table A2*:* Water quality parameters collected at various depths at the Offshore and Inshore Control Site during the dry season

OFFSHORE	DEPTH	Temperature	Conductivity	TDS	DO	pH	Atm
	1m	25.77	83	41	3.94	9.41	12.946
	3m	25.77	87	43	1.42	9.46	12.950
	6m	25.63	78	37	5.52	9.44	12.949
	10m	25.54	83	41	6.34	9.08	12.951
	11m	25.52	82	40	5.8	8.57	12.940
	12m	25.39	83	41	4.56	8.13	12.950
INSHORE							
	1m	25.85	78	42	7.03	9.15	12.98
	3m	25.87	82	42	5.25	7.83	12.985
	6m	25.79	79	38	4.60	7.68	12.997
	10m	25.54	81	40	4.0	7.60	13.009
	11m	25.58	80	40	3.67	7.58	13.011
	12m	25.56	79	39	3.12	7.56	13.013

Table A3: Water quality parameters collected at various depths at Site 1 and Site 2 (Cage Farming Area) during the first month of the wet season

	Depth	Temperature	Conductivity	TDS	DO	pH	Atm
Site 1	1m	25.5	75	37	3.98	7.8	13.19
Site 1	3m	24.94	71	35	4.71	7.91	13.181
Site 1	6m	25.05	77	39	4.33	7.55	13.123
Site 1	10m	24.6	83	41	5.33	7.19	13.058
Site 1	11m	24.67	82	41	5.51	7.14	12.995
Site 2	1m	25.34	76	37	5.22	7.87	12.97
Site 2	3m	24.9	77	39	5.36	7.81	12.964
Site 2	6m	24.64	55	28	5.33	7.68	12.941
Site 2	10m	24.36	64	32	0.555	7.52	12.877
Site 2	11m	24.44	81	41	0.28	7.3	12.877

Table A4*:* Water quality parameters collected at various depths at the Inshore Control Site during the first month of the wet season.

	Depth	Temperature	Conductivity	TDS	DO	pH	Atm
Inshore	1m	25.09	68	33	4.78	7.39	12.964
Inshore	3m	24.93	79	40	4.76	7.49	12.963
Inshore	6m	25	73	37	4.93	7.31	13.055
Inshore	10m	24.93	81	40	4.33	7.13	13.072
Inshore	11m	25.01	83	40	3.09	7.04	13.074
Offshore	1m	25.04	86	43	4.74	7.98	12.87
Offshore	3m	24.83	86	43	3.07	7.9	12.872
Offshore	6m	24.67	66	34	1.85	7.71	12.862
Offshore	10m	24.63	85	43	0.94	7.46	12.856
Offfshore	11m	24.62	75	38	0.84	7.36	12.859

Table A5: Water quality parameters collected at various depths at all sites during the second month of the wet season.

	Depth	Temperature	Conductivity	TDS	DO	pH	Atm
Site 1	1m	26.23	69	35	0.511	8.62	13.056
Site 1	3m	26.16	72	37	0.57	8.49	13.082
Site 1	6m	25.91	63	32	0.55	9.04	13.17
Site 1	10m	25.8	69	35	2.3	9	13.164
Site 1	11m	25.72	81	40	5.03	8.76	13.129
Site 2	1m	26.44	72	36	5.05	8.97	13.058
Site 2	3m	25.95	75	40	8.33	9.15	13.073
Site 2	6m	26.2	76	43	7.11	9.15	13.075
Site 2	10m	26.1	80	40	5.13	8.82	13.078
Site 2	11m	26.2	81	40	3.9	8.6	13.085
Inshore	1m	25.92	78	37	0.36	8.82	13.001
Inshore	3m	25.85	80	40	0.34	8.8	13.015
Inshore	6m	25.88	54	26	0.35	8.91	13.124
Inshore	10m	25.8	76	39	0.3	8.52	13.106
Offshore	1m	26.5	76	37	8.36	9.8	13.012
Offshore	3m	26.3	78	40	8.14	10.71	13.022
Offshore	6m	26	64	38	6.95	10.94	13.024
Offshore	10m	26.1	74	43	5.1	10.99	13.104
Offshore	11m	26	80	40	2.61	10.98	13.106

Appendix B: Experimental Design Diagram

Figure B1*:* Photograph of one of the cage fish farm setup (Sampling point)

Appendix C: Statistical Analysis

Table B1*:* ANOVA for pH

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	19.35239	2	9.676194	22.66098	1.2E-08	3.101296
Within Groups	37.14883	87	0.426998			
Total	56.50122	89				

Table B2: ANOVA table for conductivity

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	737.3722	2	368.6861	4.107051	0.019751	3.101296
Within Groups	7809.908	87	89.76906			
Total	8547.281	89				

Table B3: ANOVA for Temperature

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.002667	2	1.001333	1.858937	0.161975	3.101296
Within Groups	46.86333	87	0.538659			
Total	48.866	89				

Table B4: ANOVA Table for DO

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.149502	2	0.074751	0.058178	0.943519	3.101296
Within Groups	111.7835	87	1.284868			
Total	111.933	89				

Appendix D: Additional Figures

Figure D1: A vibrant green hue in the lake water, a visual indication of algal presence and the ecological impact of nutrient enrichment.

The greenish color of lake water is often associated with the presence of algae. Algae are single-celled organisms that utilize photosynthesis to convert sunlight into energy, producing oxygen and nutrients for the lake's ecosystem. The presence of algae causes the water to take on a greenish hue, and the high productivity of green lakes enables them to support more fish. However, poor water quality conditions in green lakes can lead to depressed dissolved oxygen levels, particularly in hot summer months, which can cause fish kills.

Appendix D2: Pictures showing some of the zooplankton species that were observed under a microscope.

Figure D2 : High-magnification image of a segmented planktonic crustacean (Sub-class Copepoda), likely a Calanoid or Cyclopoid, from the sampled water body.

Figure D3: High-magnification image (e.g., 100×) of a Copepod (likely a Calanoid or Cyclopoid), representative of the secondary producers analyzed in the zooplankton community.

Figure D4: **Representative sample of microzooplankton and macrozooplankton, including Copepods and Rotifers, observed under magnification.**

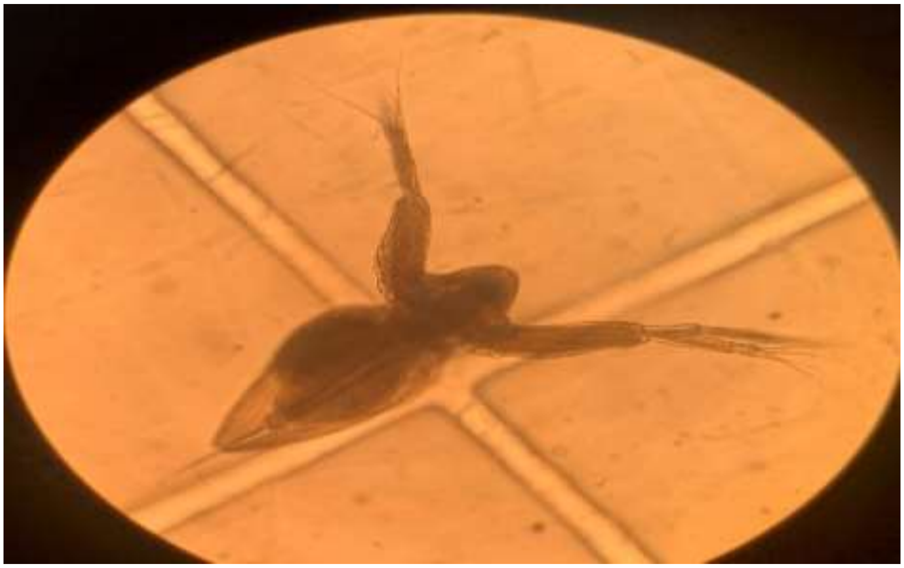

Figure D5: Microscopic image of a zooplankton, specifically a Cladoceran (Water Flea), observed during water quality sampling

Figure D6: An unfortunate scene of fish mortality in cages, possibly indicative of environmental stressors or water quality issues impacting aquaculture

Appendix E: Data Collection Process and Laboratory Observations of Zooplankton

Figure 1E: Researcher conducting essential *in situ* collection of samples to quantify water chemistry and zooplankton density

Figure 2E: Researcher enumerating zooplankton species abundance using a compound light microscope in the laboratory.

Appendix F: Ethical Clearance Letters from MAKSSREC

MAKERERE UNIVERSITY

COLLEGE OF NATURAL SCIENCES
DEPARTMENT OF ZOOLOGY, ENTOMOLOGY AND FISHERIES SCIENCES

Esther Fiskani Chirwa
Private Bag 201,
Luwinga,
Mzuzu 2,
MALAWI

Email: estherchirwa6@gmail.com

RESEARCH ETHICS AND REGULATORY APPROVAL FOR DATA COLLECTION

This letter serves to formally certify that Ms. Esther Fiskani Chirwa (Msted 0621), a registered student at Mzuzu University, has satisfied all the relevant ethical and regulatory requirements and has been granted approval to conduct data collection for her study.

The study, which was reviewed and cleared by the appropriate committees at Makerere University, specifically within the Department of Zoology, Entomology and Fisheries Sciences, is entitled: "Influence of Cage Fish Farming on Water Quality: The Case of Tende Bay, Lake Victoria."

Approval for this research was officially issued in August, 2023, following a thorough review of the protocol. Ms. Chirwa is therefore fully authorized to proceed with her fieldwork and data collection activities as outlined in her approved research protocol.

Please note that should any significant amendments to the approved methodology or protocol be required during the course of the study, further regulatory approval from the issuing authority will be mandatory prior to implementation.

We wish Ms. Chirwa every success in the implementation and completion of her study.

Signed,

....

Dr. Ronald P. D. Semyalo
Graduate Research Coordinator
Email. ronald.semyalo@mak.ac.ug

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COLLEGE OF HUMANITIES AND SOCIAL SCIENCES
SCHOOL OF SOCIAL SCIENCES
RESEARCH ETHICS COMMITTEE

Your Ref:

Our Ref: MAKSS REC 04.21.475/AR

26th November 2021

Dr. Semyalo Ronald
Principal Investigator (MAKSSREC 04.21.475)
Makerere University, College of Natural Sciences, School of Biosciences
Telephone contact: +256 701601797/+256 788 920820
Email: Ronald.semyalo@gmail.com

Dear Sir,

Initial review – Fast track
RE: Comments on proposal titled: "Mitigating the effects of environmental pollution from aquaculture on fresh water resources in Lake Victoria Basin (MEEP)"

This is to inform you that, the Makerere University School of Social Sciences Research Ethics Committee (MAKSS REC) has granted approval to the above referenced study. The MAKSS REC reviewed the proposal using the full board review on **28th October 2021.** This has been done in line with the investigator's subsequent letter addressing comments and suggestions.

Your study protocol number with MAKSS REC is **MAKSSREC MAKSS REC 04.21.475.** Please be sure to reference this number in any correspondence with MAKSS REC. Note that, the initial approval date for your proposal by **MAKSS REC was 30th April 2021**. This is an annual approval and therefore; approval expires on **29th April 2022. Please note that, final approval should be done by Uganda National Council for Science and Technology. You should use stamped consent forms and study tools/instruments while executing your field activities at all times.** However, continue d approval is conditional upon your compliance with the following requirements.

Continued Review

In order to continue on this study (including data analysis) beyond the expiration date, Makerere University School of Social Sciences (MAKSS REC) must re-approve the protocol after conducting a substantive meaningful, continuing review. This means that you must submit a continuing report Form as a request for continuing review. To avoid a lapse, you should submit the request six (6) to eight (8) weeks before the lapse date. Please use the forms supplied by our office.

Makerere University School of Social Sciences Research Ethics Committee
Valid Thru.
29 APR 2022
APPROVED

Please also note the following:

- No other consent form(s), questionnaires and or advertisement documents should be used. The Consent form(s) must be signed by each subject prior to initiation of my protocol procedures. In addition, each research participant should be given a copy of the signed consent form.

Amendments

During the approval period, if you propose any changes to the protocol such as its funding source, recruiting materials or consent documents, you must seek Makerere University School of Social Sciences Research and Ethics Committee (MAKSS REC) for approval before implementing it.

Please summarise the proposed change and the rationale for it in a letter to the Makerere University School of Social Sciences Research and Ethics Committee. In addition, submit three (3) copies of an updated version of your original protocol application- one showing all proposed changes in bold or "track changes" and the other without bold or track changes.

Reporting

Among other events which must be reported in writing to the Makerere University School of Social Sciences Research and Ethics Committee include:

i. Suspension or termination of the protocol by you or the grantor.
ii. Unexpected problems involving risk to participants or others.
iii. Adverse events, including unanticipated or anticipated but severe physical harm to participants.

Do not hesitate to contact us if you have any questions. Thank you for your cooperation and commitment to the protection of human subjects in research.

The legal requirement in Uganda is that, all research activities must be registered with the National Council for Science and Technology. The forms for this registration can be obtained from their website www.unsct.go.ug

Please contact the Administrator of Makerere University School of Social Sciences Research and Ethics Committee at makssrec@gmail.com OR [illegible]@yahoo.co.uk or telephone number +256 712 207926 if you counter any problem.

Yours sincerely,

Makerere University School of Social Sciences Research Ethics Committee
Valid Thru.
29 APR 2022
APPROVED

Dr. Stella Neema
Chairperson
Makerere University School of Social Sciences Research and Ethics Committee

C.c.: **The Executive Secretary, Uganda National Council for Science and Technology**