ECOLOGICAL CARRYING CAPACITY AND GROWTH PERFORMANCE OF NILE TILAPIA (*Oreochromis niloticus*) IN CAGE AQUACULTURE WITHIN KADIMO BAY, LAKE VICTORIA, KENYA

BY

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DECLARATION

Declaration by the Candidate

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DEDICATION

To God Almighty who create something out of nothing

To my beloved family in Sierra Leone, who stood with me in spirit while I was physically away.

To my beloved family in Kenya, who stood with me both physically and spiritually while putting this piece of work together.

And

To the memory of my late Father, Sahr Sellu Sulow Mawundu and his beloved wife Sia Sitta Mawundu and all my siblings for their support.

This is my only way of appreciating all your relentless contributions from my Primary education to this level.

Your thoughtfulness got me this far

In the beginning was the word, and the word was with God, and the word was God. (John 1:1)

ABSTRACT

Fish production in the wild is decreasing globally due to a number of factors including overfishing, pollution, invasive species, and climate change effects. In Kenya, fisheries contribute less than 1% to the national GDP with an annual production of about 400, 000 mt against a demand of about 600,000 mt. Aquaculture production through innovative approaches such fish cage farming, has the potential to bridge the demand deficit. Despite the high potential for cage fish farming in Kenyan water bodies, there have been few studies focused on the effects of fish cages on water quality and trophic status, the nutrient carrying capacity of cage sites, and the appropriate stocking densities for cages in the water bodies. This study therefore was aimed to bridge these data gaps in order to facilitate sustainable management of the increasing fish cage farming of the Nile tilapia (*Oreochromis niloticus*) in Lake Victoria. Sampling for physico-chemical and biological variables, including nutrient load, was conducted from January to October 2021, at five fish cage sites and a control site within the Kadimo Bay,Lake Victoria, Kenya. The Carlson's Trophic State Index (CTSI) was used to classify the trophic state of the cage sites in the bay, and TN: TP ratio used to determine nutrient limitation in the bay. Fish cage optimum stocking density studies were carried in the bay from February to September 2022. *Oreochromis niloticus* fingerlings with initial mean (±SD) weight of 5.5 ± 1.72 g, were stocked at densities of 50, 75, 100, 125 and 150 fish m^3 in replicate cages and growth and water quality changes monitored. The TP assimilation capacity and fish production potentials for the five cage sites within the bay were determined using a mass-balanced model. Results showed higher electrical conductivity (112.84 ± 1.94 µS cm^{-1}) at cage sites compared to a Control site (97.53 ± 4.17 µS cm^{-1}), similar variations were observed for nitrates and chlorophyll-a. However, 15 physico-chemical variables (DO, Temp., pH, TDS, Turb., TSS,POM, SRP, NO_2^-, NO_3^-, TN, TP, NH_3, NH_4^+, SiO_4^{4-}) did not vary significantly between the cage and control sites. The bay was evaluated as being in a light eutrophic state. Nitrogen as opposed to Phosphorus, was indicated to be the limiting nutrient for primary production in the bay. Growth performance results showed that fish stocked at lower densities (D50 & D75) had the highest growth performance in terms of mean weight gain (545.0 ± 15.81 and 527.4 ± 13.80 g, respectively). The Control treatment (D100), which is the normal stocking density used by cage fish farmers, showed intermediate mean weight gain (348.2 ± 11.48 g) which was significantly lower ($p < 0.05$) than for the D50 and D75 treatments. The feed conversion ratio (FCR) was lowest at D50 (1.2 ± 0.02) and highest at D150 (2.9 ± 2.01). Carrying capacity results, showed for all the five cage sites within the bay, the TP assimilation capacity was exceeded by the TP released by the fish cages. Additionally, the maximum estimated fish production capacities were much less than the current fish production levels for all the sites. Overall, although the results of this study showed cage aquaculture is not a current challenge to the water quality of the bay, regular monitoring is recommended to inform sustainable aquaculture development in the bay and the lake. It is recommended for fish farmers to stock fish at lower densities of 50 fish m^3 in order to maximize sustainable economic and environmental benefits of the cage culture system. Policies governing aquaculture production in the lake should be reviewed or enacted in order to include evidence-based information on environmental quality, sustainable production levels, and nutrient carrying capacity of the lake.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

$[P]_{C}$: Measured phosphorus

$[P]_{I}$: $_{M}$aximum allowable phosphorus load for fish culture.

°C: Degree Celcius

µg: Mirogrammes

µS: Microsimens

A: Surface Area

Adr: Long-term average inflow from catchment surface runoff

ANOVA: Analysis of Variance

APHA: American public health association standard methods for the examination of water and waste water. APHA-AWWA-WEF, 2005

BCR: Benefit Cost Ratio

BMU: Beach Management Unit

BOD: Biological Oxygen Demand

CC: Carrying Capacity

CCNY: Carnegie Cooperation of New York

Chl-a: Chlorophyll-a

Cm: Centimetres

COD: Chemical Oxygen Demand

CTSI: Carlson Trophic State Index

DO: Dissolve Oxygen

EAA: Ecosystem Approach to Aquaculture

EC: Electrical Conductivity

EU: European Union

Ev: Evaporation from the lake

FAO: Food and Agricultural Organisation of the United Nations

FCR: Feed Conversion Ratio

GTA: Graduate Teaching Assistant

H: Height

H^{+}: Hydrogen ion Concentration

ISA-UoE: International Student Association, University of Eldoret

Kg: Kilogrammes

KMFRI: Kenya Marine and Fisheries Research Institute

Ksh: Kenyan shillings

L: Length

L: Litre

Lfish: Cage site carrying capacity (maximum assimilation load) of total Phosphorus (mg m^3 $year^{-1}$).

MCS: Monitoring Control and Surveillance

mg: Milligrammes

mm: Millimetres

MT: Metric Tonnes

NH_3: Ammonia

NH_4^+: Ammonium ion

NO_2^- : Nitrite

NO_3^-: Nitrate

Ø: Flushing coefficient, a measure of the water replacement rate at a site

Pe: TP released into the environment from a ton of fish produced (kg of TP per ton of fish production).

$P_{feed:}$ TP in fish feeds (kg ton^{-1})

$P_{fish:}$ TP incorporated into the body of whole fish (kg ton^{-1})

pH: Acidity

POM: Particulate Organic Matter

Pr: Precipitation into the lake

Q: Average water debit

R: Phosphorus retention coefficient

$R_{fish:}$ Proportion of total phosphorus left in sediments as a result of Feeding fish in the cages

RUFORUM: Regional Universities Forum for Capacity Building in Agriculture

SD: Seechi Disk

SD:	Standard Deviation
SiO_4^{4-}:	Silicates
SRP:	Soluble Reactive Phosphorus
TDS:	Total Dissolve Solids
Temp.:	Temperature
TN:	Total Nitrogen
TP:	Total Phosphorus
TS:	Trophic State
TSI:	Trophic State Index
TSS:	Total Suspended Solids
USA:	United States of America
UV:	Utraviolet
V:	Volume
W:	Width
WHO:	World Health Organization
X:	The net proportion of total phosphorus lost permanently to the Sediments
Z:	Average depth of a cage site
Δ [P]:	Total phosphorus allocation load, obtained from the difference between measured phosphorus $[P]_c$ and the maximum allowable Phosphorus load $[P]_i$ for fish culture.

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CHAPTER ONE

INTRODUCTION

1.1 Background

Current population growth and increase of per capita fish consumption will demand water resources to be used more efficient in terms of food production on a global scale (Halwarth *et al.*, 2007). The rising food demand is putting more pressure on wild fisheries resources (Worm *et al*., 2009) and cage fish farming is one of the alternatives increasingly being used to enhance fish production particularly in the tropics (FAO, 2010). Cage fish farming uses ecosystem microbial agents for the breakdown of organic matter, recycling of nutrients and supply of oxygen (Beveridge, 2004). However, a certain level of fish biomass may exceed the system's capacity to function normally leading to a breakdown in ecosystem function through negative feedbacks such as eutrophication (Beveridge, 2004; Pillay, 2008; David *et al.*, 2015), a process by which nutrients load especially phosphates and nitrates leads to increased algal production causing changes in ecosystem function and structure (Volleinweider *et al*., 1998). Cage aquaculture often results in water quality changes and pollution through unconsumed, undigested and metabolic wastes from fish cages (Aura et al., 2018). Consequently, appropriate cage densities and fish production levels are required in order to provide optimum production without jeopardizing water quality and ecosystem function (Njiru et al., 2018). The concept of ecological carrying capacity that sets maximum limit for aquaculture production is a potential policy and management tool for sustainable cage aquaculture and resilience of fresh water ecosystems to perturbations (Dillon & Rigler, 1975; Ross *et al*., 2013; David *et al*., 2015).

Aquaculture is rapidly increasing in African inland aquatic ecosystems (Njiru *et al*., 2004; Rothuis, 2014). In Lake Victoria for example, it is estimated that there are in excess of 4,000 cages on the Kenyan side of the lake (Njiru *et al*., 2018; Orina *et al*., 2018). Despite the popularity of the system, there have been little or no scientific studies to evaluate the possible effects of cage farming of *O. niloticus* on water quality parameters and the trophic status of the cage sites in Lake Victoria. This information is, however, necessary to determine desirable stocking densities for the cages in the lake that provides optimal fish production and returns without compromising environmental quality of the waters. Such optimal fish production should not jeopardize the ecological functions of the lake and should allow for sustainability and resilience of the ecosystem to perturbations.

Sustainable cage culture production should focus on estimating the quantity of fish production that can be sustained by the environment without dramatic change in ecological processes, ecosystem services, species populations and community structure (Beveridge, 2004; David *et al*., 2015). Despite the increasing use of fish cages in African lakes and reservoirs, there are hardly any regulations and management protocols aimed at sustainable aquaculture production within the framework of an ecosystem approach to fisheries management (Frankic & Herhner, 2003; Clottey *et al*., 2016; Aura *et al*., 2018). Management of cage aquaculture require provision of scientific data on; water quality variability, feeding regimes, stocking densities, in addition to socio-economic information aimed at minimizing user conflicts. Water quality monitoring and assessment programs at cage aquaculture sites are necessary to inform public policies on aquaculture production and development in natural aquatic systems (Aura *et al*., 2017). Water quality is a critical determinant of ecosystem structure and functioning through its influence on productivity, physiological and behavioral activities of aquatic organisms (Scheffer *et al*., 2001) and species abundance (Wootton, 1991). Cage aquaculture has the potential to affect water quality of aquatic systems through uneaten fish feeds and wastes with a likelihood of causing eutrophication (Pillay, 2005). Uneaten feed and fish waste contribute to phosphorous and nitrogen enrichment, ultimately leading to eutrophication effects such as, increased turbidity due to algal biomass and deoxygenation with potential for fish kills and biodiversity loss (Vollenweider *et al*., 1998; Ngupula and Kayanda, 2010; Sayer *et al*., 2016).

Consequently, continuous monitoring of water quality variables around aquaculture installations is required in order to advise on aquaculture development and management (Aura *et al*., 2018; Musinguzi *et al*., 2019). This requirement is particularly necessary for Lake Victoria where aquaculture installations continue to increase rapidly without any environmental monitoring initiatives (Aura *et al*., 2017; Njiru *et al*., 2018) and where eutrophication is a major challenge (Koldings *et al*., 2008). Additionally, the extent to which Lake Victoria ecosystem is limited by nutrients is not known and the addition of Phosphorous (TP) and Nitrogen (TN) through feeds may affect nutrient balance in the lake (Beveridge, 1984), making it necessary to continuously evaluate the TP: TN ratios around fish cages. There have been studies reporting the effect of experimental cages on water quality in Lake Victoria-Tanzania (Kashindye *et al*., 2015), however, studies documenting the effects of cage aquaculture on water quality and ecosystem functioning in African lakes are generally scarce.

The Nile tilapia (*O. niloticus*) is a good candidate for cage aquaculture because of a number of reasons including; its omnivorous feeding habits, ability to survive in deteriorating water quality, ease of breeding under confined environmental conditions as well as under diverse types of aquatic ecosystems (Pillay, 1990). However, even with a good aquaculture candidate, certain parameters like stocking density, water quality and feeding regime are important for optimal growth and yield (Mwainge *et al*., 2021; Nyakeya *et al*., 2022). Increasing stocking density may result in negative consequences such as, augmenting stress, disease prevalence and mortality, and even decreasing feed conversion ratio in farmed fish (Asase, 2013; Owuor *et al*., 2019; Oyier *et al*., 2021), thereby requiring optimal density determination. The optimal stocking density will, however, vary between species, environmental conditions and culture systems (Schmitton & Rosati, 1991; Ngodhe, 2021).

This study evaluated, the water quality parameters within a high-density fish cage area (Kadimo Bay) in the Winam Gulf of Lake Victoria (Kenya) and compared the values with the expected ranges for ecosystem functioning. The numeric Carlson's Trophic State Index (CTSI) (Carlson & Simpson, 1976; Carlson, 1977) was used to evaluate the trophic status of the cage sites in the bay and to test a hypothesis of "cage influence on trophic status of the bay". Additionally, the study evaluated the relative limitation of TP and TN ratio to productivity in the bay, and tested the commonly held hypothesis of "TP limitation in freshwater lakes" (Volleinweider, 1968; Schindler, 2012). The study further determined the effects of stocking density on growth and survival of *O. niloticus* in experimented cages within Kadimo Bay and used a mass-balanced model based on phosphorus load (Dillon & Rigler, 1975), to estimate the phosphorous assimilation capacity of five cage sites in the bay. The results of this research have potential applications in policy development for sustainable management of cage fish production and aquaculture development in Lake Victoria, for sustenance of livelihoods and ecological services of the lake.

1.2 Statement of the problem

Alteration of fisheries management structure has pushed towards more rigid measures to fisheries licensing in many countries. Nevertheless, only in a small number of countries has the assessment of carrying capacity at system scale been given consideration on the basis of defining and quantifying the possible fish farm areas as a first step before local agreements for fish farm investment (Ferreira *et al.,* 2008a). Cage fish farming in Lake Victoria is not based on knowledge from carrying capacity assessment. The implementation of the Ecosystem Approach to Aquaculture (EAA) (Garcia, 2009) at various geographic regions necessitates the compromise of three objectives that comply with the EAA protocols: (i) environmental integrity; (ii) socio-economic wellbeing; and (iii) governance, in addition to multi sectoral planning (FAO, 2010). These three objectives of EAA and their relative importance may differ between countries and across continents, making it difficult to single out a uniform standard of compliance with regards to limits and thresholds in aquaculture.

Lake Victoria's fish stocks are struggling to keep up with demand (Njiru *et al*., 2004). For instance, stocks and catches of the Nile Perch have declined from 340,000 tons in 1990 to about 251,000 tons in 2014 (Munguti *et al.*, 2014). In 2010, there were about 42.2 million people depending on the lake and it was projected that by 2030, the number of people depending on the lake will approximate to 76.5 million (Munguti *et al*., 2014). About 3 million people rely directly on fisheries for food and about 10 million East Africans rely on fisheries for their livelihoods (Munguti *et al*., 2014; Cowx & Ogutu-Owhayo, 2019). There is also an international demand for the lake's fish catches of leading commercial species like the Nile perch and *O. niloticus* which are now caught primarily for export to Europe and Asian markets (KMFRI, 2017). These challenges to natural fish stocks sustainability are compounded by overfishing and illegal fishing activities. The increased demand on wild fish stocks of Lake Victoria calls for management measures to conserve stocks. Cage fish farming is one such measure that has the potential to supplement the lake's production and reduce pressure on wild fish stocks. Nevertheless, sustainable cage fish farming in Lake Victoria calls for an assessment of production carrying capacity, evaluation of the influence of cage culture on water quality and trophic status of cage sites in the lake and an evaluation of best culture practices for sustainable production of *O. niloticus* in the lake.

1.3 Justification

Scientific information is required for the development of policy for cage fish farm establishment in aquatic environments. There is need for proper planning of cage aquaculture in the lake to be based on scientific data that promotes sustainability (Munguti *et al*., 2014; Adeleke *et al*., 2018). Such scientific data should have essential components that utilize science-based approaches for policy development and ecosystem-based approaches for integrated fisheries management (Adeleke *et al*., 2018).

The high price of fish feed, lack of knowledge on feed fed to a given fish biomass in a production cycle are problems associated with feed use in cage aquaculture (Adeleke *et al.*, 2018; Cowx & Ogutu-Owhayo, 2019) and requires evaluation with regard to culture system. The determination of optimal stocking density for growth performance of *O. niloticus* in Lake Victoria is necessary for sustainable cage fish production. Cage fish farming requires the provision of scientific knowledge that will be useful for fish farmers to quantify the amount of feed to apply without compromising the ecological services of the lake. In order for a production system to remain in harmony with the environment, there is needs for proper regulation and collaboration between all stakeholders. Although cage fish farming on the Kenyan side of Lake Victoria is rapidly increasing (Aura *et al*., 2018), there is need to provide data that will regulate feeding regimes, control cage densities and site carrying capacities of cage sites. Additionally, the data will help maximize production and evaluate both ecological and economic sustainability of cage fish farming. This research work was aimed at generating information useful for sustainable *O. niloticus* production in Lake Victoria.

1.4 Objectives of the study

1.4.1 Main Objective

The main objective of this study was to provide data and information that will be applied in sustainable management of cage aquaculture production in Lake Victoria, Kenya, with potential application in other water bodies.

1.4.2 Specific Objectives

The following were the specific objectives of this study:

1. To determine the influence of cage farming on water quality parameters and trophic status of selected cage sites in Kadimo Bay of Lake Victoria, Kenya.

2. To evaluate the Total Phosphorous assimilation capacity at fish cage sites in Kadimo Bay of Lake Victoria, Kenya.

3. To evaluate the Nile tilapia production carrying capacity of fish cage sites in Kadimo Bay of Lake Victoria, Kenya.

4. To evaluate the effect of stocking density on the growth performance and survival of the Nile tilapia (*O.niloticus)* in experimental cages in Lake Victoria, Kenya.

1.5 Hypotheses

This study was guided by the following hypotheses:

$H0_1$: Cage fish farming in Lake Victoria has no influence on water quality and trophic status of the cage sites in Kadimo Bay, Lake Victoria. Kenya.

$H0_2$: The Total Phosphorus assimilation load of the cage sites in Kadimo Bay has not been exceeded.

$H0_3$: The Nile tilapia production carrying capacity of Kadimo Bay in Lake Victoria has not been exceeded.

$H0_4$: The growth performance and survival of the Nile tilapia does not differ under different cage stocking densities.

CHAPTER TWO

LITERATURE REVIEW

2.1 Global Aquaculture production

The world fish production from fish farming has shown a steady growth in the past few decades (Halwart & Moehl, 2006). This production has contributed significantly to the supply of fish to meet the protein needs of the growing global population. Fish farming now contributes about half of the global food fish supply (Delgado, 2003; Kassam, 2014). With this growth, it is possible that fish farming in the future will produce most of the fish needed to meet the protein needs of the human population, than the contribution coming from the wild capture fisheries (Delgado, 2003; Blow & Leonard, 2007). Fish farming which began as an Asian food production system in freshwater aquatic environment is now practiced in all countries around the world; in all water resources with the culture of both shell and fin fishes (Costa-Pierce et al., 1988; Ndonga et al., 2020). At the beginning, fish farm practices were done on a small scale, nonprofit oriented and for the purpose of subsistence, today the practice is profit oriented and is done on large scale for commercial reasons (Azim et al., 2003; Kaunda et al., 2003). It is widely believed that fish farm practice today contribute significantly to the growing need of animal protein supply for the world population and national development, while at the same time supporting livelihoods of local communities (Njiru et al., 2018).

Global fish farming has grown significantly over the last five decades from a production of one million tons in the 1950's and 1960's to fifty million tons in 2005 (FAO, 2003; Delgado, 2003; Halwart & Moehl, 2006) and about 114.5 million tons in 2000 with an estimated first sale value of US$160.2 billion (Delgado, 2003; Blow & Leonard, 2007).

In 2020, the global freshwater aquaculture production was about 54.4 million tons representing 44.4% of world aquaculture production of fish and algae (Delgado, 2003; Owour et al., 2019). A mean annual growth rate of 8.8% and current production at the farm gate price of 70.3 million US$ was noted and rising steadily as farmers product goes along the value chain to the consumers (Delgado, 2003; Gondwe et al., 2011). The Peoples Republic of China contributed approximately 67.3% (32.4 million tons) in the early 2000 and 27.3% contribution by the remaining Asia-Pacific region (Kelly et al., 1998; Delgado, 2003; Munguti et al., 2014). Western Europe contributes 4.2% or 200 million tons price at US$ 6.2 million (Delgado, 2003). The rest of Europe contributed 270 thousand tons or 6.6%, South America, the Caribbean and North America contributed 1.3% amounting to 2.9 million tons (Delgado, 2003; Nagoli, 2020). Production from Africa and the Middle East accounts for 1.2 million tons (0.2%) (Delgado, 2003; Blow & Leonard, 2007).

World fish farm production maintained its growth in 2020 regardless of the global Covid 19 pandemic with variation among countries and regions (Azim et al., 2003). The fish farm production in 2020, constitute 37.5 million tons of aquatic protein source from animals for human consumption, 35.1 million tons of aquatic plants for human consumption and other uses, 700 tons of shell and pearls for recreation use totaling 122.6 million tons in 2020 (Delgado, 2003; FAO, 2010). This production is 6.7 million tons rise from 115.9 million tons in 2018 (Delgado, 2003). Based on farm gate price it has an estimated value of US$ 281.5 billion in 2020, a rise of US$ 18.5 billion from 2018 and US$ 6.7 billion in 2019 (FAO, 2010; Asare, 2013). Global fish farm production of protein source from aquatic animals, (combined fisheries and aquaculture production) attain recorded height of 214 million tons in 2020 constituting 178 million tons of aquatic animals and 36 million tons of aquatic plants (Delgado, 2003; FAO, 2010). The quantity meant for human use with the exception of aquatic plants was 20.2kg per capita which is in excess of 9.9 per capita in the 1960s (Delgado, 2003). An average of 58.5 million people were working in the primary sector including people working just to feed themselves and their families. Up to 600 million livelihood rely partly on wild fisheries and aquaculture (Delgado, 2003; Halwart & Mohel, 2006; FAO, 2010). Global trade of wild fisheries products produced about US$ 151 billion in 2020, lower than the record high of US$ 165 billion in 2018 (Delgado, 2003; Kassam, 2014).

The culture of aquatic plants largely come from the Asia Pacific region amounting to 99.3% of the global production, the culture of cyprinids is largely practiced in south-east Asia, while the rearing of the high valued marine fish is practiced in east Asia (Delgado, 2003). On the global scale 97.5% of the cyprinids, 88.6% of the crustaceans, 95% mollusc are produced in the Asia-Pacific region (Delgado, 2003; FAO, 2010 ;).

The western part of Europe produce roughly 53.1% of the salmonids, while 45% production of the salmonids comes from South America (Dahlback & Gunnersson, 1981). The channel catfish (*Ictalus puntatus*) and the salmon fish are the most preferred species for aquaculture production on the American continent (Phiri et al., 2018). In the Caribbean region and the South American, the culture of salmonids have surpassed the culture of shrimps and other shellfish species. This was due to the rapid growth of salmon farming in Chile and the widespread diseases outbreak in shrimp farms in Latin America (Nagoli, 2020).

Driven by the rapid expansion in Chile, China and Norway in 2020, the global fish farm production rose in all regions with the exception of Africa as a result of reduced production in the two leading aquaculture producers, Nigeria and Egypt (Delgado, 2003). The remaining Sub-Sahara Africa recorded a 14.5 % growth from 2019, while Asia continue to be the leading producer in aquaculture with 91.6% production of the total fish farm production globally (Delgado, 2003; Ndanga et al., 2013).

Global needs for protein source from the aquatic environment has shown a steady rise in more recent times and will continue to grow. The global demand for food from the aquatic environment has grown from an average annual rate of 3.0% since 1961 relative to population increase of 1.6 % (Delgado, 2003; Rurangwa et al., 2015). On the basis of per capita fish consumption, it shows an increase on average from 9.9kg in the 1960s to record peak of 20.5 kg in 2019, with a slight fall to 20.2 kg in 2020 (Njiru et al., 2004; Asare, 2013). It is projected that by 2030, increasing income earning and improvement in technology will increase the per capita fish consumption to 21.4 kg (Delgado, 2003). However, aquatic resources are on a decline due to increasing fishing technologies, climate change and poor control and management policies at government levels (Kelly et al., 1998). The portion of fisheries resources remaining biologically sustainable has fall to 64.6% in 2019, which is 1.2 % less than in 2017 (Delgado, 2003). Nevertheless 82.5 % of the catches in 2019 comes from biologically sustained species which is 3.8 % better than 2017 (Kelly et al., 1998; Delgado, 2003). Sustainable fisheries management has shown to be effective in stock enhancement and rising catch within the confines of ecosystem boundaries (Ben Yami, 1978).

Africa with all its abundant water resources has yet to record any significant production in the aquaculture industry. However, some improvements are known to be happening in Sub-Sahara Africa countries, even though over dependence on wild captured fisheries, lack of scientific knowledge and personnel’s for the aquaculture industry are all contributing factors towards the low production in the industry (Azim et al., 2003). In Africa, the leading players in the aquaculture industry are Egypt followed by Nigeria and Uganda (FAO, 2010). The economic viability of fish farming varies according to regions.

Cage aquaculture started in Africa as a way for fishermen to keep their catch until they are ready for the market (Masser, 1998; Blow & Leonard, 2007). At the onset cages were fabricated with wood of foliage materials and fish were fed with trash. In the 1950s more advanced cage culture practice began with the use of synthetic materials for cage fabrication in Sub-Saharan Africa (Seymour, 2001). In Africa, research on cage aquaculture began in the 1960s as pond culture was the only viable aquaculture practice before then. Cage aquaculture was experimented on trial basis in Sub-Saharan Africa in the 1980s when the need for aquaculture development grew and received government attention as part of the national development agenda (Masser, 1998). In recent times the general development plans of most African countries has come to view aquaculture as an independent sector (FAO, 2001).

Cage aquaculture production has been introduced in Cote d’Ivoire, Ghana, Kenya, Malawi, Rwanda, South Africa, Uganda, Zambia and Zimbabwe with commercial cage aquaculture developing in Ghana, Kenya, Malawi, Uganda, Zambia and Zimbabwe at the moment (Rurangwa et al., 2015). Pen culture and Marine, brackish water cage aquaculture is not being practiced in the region. The Nile tilapia (*O. niloticus*) is the only fish being farmed in cages in the region (Blow & Leonard, 2007).

2.2 Aquaculture contribution to food security

Fish farming plays a significant role in efforts around the world to combat the problem of malnutrition, hunger and the enhancement of livelihoods through the provision of fish and fish products for human consumption (Muller & Varadi, 1980). Fish farming is also important toward the development of local communities in developing countries, through the provision of employment opportunities and enhancing the economic viability of the resources used (Costa-Pierce et al., 1988). Based on the reports from the United Nations Food and Agricultural Organization (FAO,2008), fish farming created roughly twelve million permanent jobs in Asia and contributed largely to the national development in many third world nations in South America, Asia and Sub-Sahara Africa (Delgado, 2003; Nagoli, 2020).

With well-planned policies at government levels, the fish farm sector is prepared to meet the growing needs of animal protein supply from fish in the coming decade for the realization of global food security (Costa-Pierce et al., 1988). The supply of good quality animal protein from fish and fish products and its availability on the markets and affordability by consumer households are all connected with one another for achieving global food security (Munguti et al., 2014). Concerning the food supply on the market, fish farming enhances the supply of fish through production of aquatic animals such as shell and fin fishes (Kelly et al., 1998). Fish farming provide a nutritious food through the provision of essential amino acids that are necessary for the growth and development of human population around the world (Kaunda et al., 2003). The intake of fish and fish products has significantly helped in preventing heart diseases, malnutrition and other diseases related to low protein intake (Azim et al., 2003). In this regards fish farming plays an important role in the growth and development of the human body. Knowledge in the area of importance of fish and fish products has led to rising consumption of fish and fish products in the developed world more than developing countries (Byron et al., 2011).

In 2002, the contribution of protein supply from fish was approximately twelve percent (12 %) of the total global protein consumption (Gondwe et al., 2011). The provision of fish from the aquaculture sector is necessary but not in adequate supply towards global food security (Kelly et al., 1998). In sub-Saharan Africa, the ability of buying fish on the market is of primary concern for the consumers, due to lack of money and their low income earnings. Raising the supply of fish from the aquaculture sector will lead to an increasing consumption of fish and fish product on the domestic market, thereby enhancing their affordability for consumers (Byron et al., 2011). Besides individual and local community development, fish farming at small-scale level contribute to economic growth, through tax and revenue collection (Aura et al., 2018). Infrastructural development and quality human capital development lead to improvement in labor and capital that promotes local development. With the current advancement in technology and the availability of resources, fish farm production is likely to increase in a more sustainable manner (Azim et al., 2003). This can be only achieved from the social and economic gains added to the larger local community. The challenge for government and development partners towards sustainable fish farm development is the creation of an enabling environment for fish farm investment, growth and development (Costa-Pierce et al., 1988). This enabling environment needs a multi disciplinarily approach based on scientific knowledge and rational government policies that will contribute significantly toward the rapid growth and development of the sector (Blow & Leonard, 2007; Byron et al., 2011).

2.3 Managing Environmental Issues in the Aquaculture Sector

The adverse environmental impacts affecting the aquaculture sector are of primary concern in the last ten years (Munguti et al., 2018). In situation where the social carrying capacity of fish farm establishment are not well received by local communities, the environmental challenges are of concern to both government and development partners (Byron et al., 2011). These challenges will be more relevant in the future as aquaculture growth continue to rise. Furthermore, the challenges will escalate by the rising need for fish and fish products because of the high competition in the fish farm practice sector (Gondwe et al., 2011). These will be exuberated by climate change at various levels in different regions (Kelly et al., 1998). With weak policy development at both local and national level coupled with poor management practice, the possibility of conflict among resource users is inevitable (Azim et al., 2003). Consequently, the poor and weak resource users will be eliminated or disadvantaged in the use of the available resources for the practice of aquaculture (Owour et al., 2019). Poor management practice and weak control measures in the aquaculture sector will lead to low economic benefits realized from the sector causing the exploitation of these resources below their current carrying capacity (Orina et al., 2018). The strong public opinion regarding adverse environmental consequences in respect of fish farm practice that begin a few years ago are now more intense and a lot is being done to address the adverse environmental impact of aquaculture by making fish farmers to be more considerate in their activities (Phiri et al., 2018). Responsible fish farm practice can be of great economic benefit to the society with little or no adverse environmental consequences (Asiedu et al., 2016). It is recognized that fish farm practice can have a positive impact on the environment by mitigating the effects of nutrients from agricultural runoffs discharged in the aquatic environment that contributes towards primary production (Halwart & Moehl, 2006; Byron et al., 2011).

2.4 Overview of Cage Aquaculture

2.4.1 Origin and principles of cage aquaculture

The culture and production of aquatic animals in cages is a relatively recent aquaculture innovation. Even though the beginning of the use of cages for holding and transporting aquatic animals for short periods can be traced back almost two centuries ago to the Asian region (Pillay & Kutty, 2005) and may have started even earlier as part of the indigenous practice of fishermen living on boats in the Mekong river. The commercialization of marine cage aquaculture started in the seventies in Norway as a result of the rise and development of salmon farming (Beveridge, 2004). Cage aquaculture has shown a rapid development in the last twenty years and is currently experiencing a rapid advancement in response to the pressure from globalization and the growing demand for aquatic products in both third world and first world countries (Halwart & Moehl, 2006).

It has been projected that fish consumption in third world countries will rise by 57% from 62.7 million metric tons in 1997 to 96.6 million metric tons in 2020 (Delgado et al., 2003). Comparing this, fish consumption in the developed world will rise by only 4% from 28.1 million metric tons in 1997 to 29.2 million metric tons in 2020 (Munguti et al., 2014). Continuous population growth, rising affluence and urbanization in third world countries are causing major changes in the supply and demand for animal proteins from livestock and fish (Quagrainie et al., 2007). As the case with terrestrial agriculture, the alteration within the aquaculture sector towards the development and the use of intensive cage aquaculture system was driven by a combination of factors, including the rising competition faced by the sector for the available resources (Tilman et al., 2002; Foley et al., 2005), the need for aquaculture commercialization and the drive for rising production per unit area (Halwart & Moehl, 2006). Also, the need for appropriate site selection for cage installation has made the sector to access and expand into new untapped open waters such as lakes, reservoirs, rivers and coastal brackish and marine offshore waters.

There is little or no official data for global aquaculture production from the cage aquaculture sector. However, there is some information on the number of cage culture units and statistics on production reported by some countries (Blow & Leonard, 2007). In total sixty two (62) countries reported data on cage aquaculture production in 2005; twenty five (25) countries directly provided cage culture production data, another thirty seven (37) countries reported production data from which cage production can be derived (Asiedu et al., 2016). Of the sixty two (62) countries and regions, thirty one (31) countries reported relevant data to FAO both in 2004 and 2005 (Halwart & Moehl, 2006). The total cage aquaculture production from these sixty two (62) countries amounted to 2, 412, 167 ton with the exception of production from the People's Republic of China (Nagoli, 2020). Based on this report, the key players in cage aquaculture production in 2005 included Norway (652, 306 tons), Chile (588,060 tons), Japan (272,821 tons), United Kingdom (135,255 tons), Vietnam (126,000 tons), Canada (98, 441 tons), Turkey (78, 924 tons), Greece (76, 577 tons), Indonesia (67, 672 tons), and the Phillippines

(66,249 tons) (Halwart & Moehl, 2006). The total cage aquaculture production in mainland People's Republic of China in 2005 was reported as 991, 555 tons (704, 254 tons from inland cages and 287, 301 tons from coastal cages) (Halwart & Moehl, 2006).

2.4.2 Major cultured species, cage culture systems and culture environments

Commercial cultivation of fish through cage aquaculture systems has been limited mainly to the cultivation of high-value species or compound-feed-fed finfish species, including the salmon fish (*Salmon salar*, *Salmon spp and Salmon trutta*), most major coastal and inland carnivorous fish species (including Japanese amberjack, red seabream, yellow croaker, European seabass, gilthead seabream, cobia, sea raised rainbow trout, Mandarin fish, snakehead) and an ever increasing proportion of omnivorous freshwater fish species (including Chinese carps, tilapia, Colossoma, and catfish) (Halwart & Moehl, 2006). However, cage aquaculture systems practiced by cage fish farmers are at the moment as different as the number of species being cultured, varying from indigenous family-owned operated cage aquaculture practice typical of most Asian countries (Pillay & Kutty, 2005; De Silva & Phillips, 2007) to more advanced commercial cages used in Europe and the Americas (Nagoli, 2020) .

On the basis of species diversity, an estimated 42 families of fish are reared in cages, but just five families (Salmonidae, Sparidae, Carangidae, Pangasiidae and Cichlidae) constitute 90% of the overall production and one family (Salmonidae) contributes 66% of the overall production (Pillay & Kutty, 2005). At species level, there are about 80 species been cultured in cages. Of these, one species (*Salmo salar*) contribute for about half (51%) of all cage aquaculture production and other four species (*Oncorhynchus mykiss, Seriola quinqueradiata, Pangasius spp. and Oncorhynchus kisutch*) contribute roughly one fourth (27%) (Halwart & Moehl, 2006). Ninety percent (90%) of the overall production is from only eight species (*Oreochromis niloticus*, *Sparus aurata*, *Pagrus auratus and Dicentrarchus labrax)* in addition to those mentioned above (Halwart & Moehl, 2006). The balance 10% of the overall production comes from the remaining 70+ species. From regional review papers, the Atlantic salmon is presently the most largely cage-cultured fish species by volume and value (Blow & Leonard, 2007). Reports on aquaculture production of this cold water fish species rose over 4 000 fold from 294 tons in 1970 to 1, 235, 972 tons in 2005, valued at US$4, 767, 000 million), with large-scale production of over 10, 000 tons (Halwart & Moehl, 2006). Production is at the moment limited to a handful of countries, including Norway, Chile, the United Kingdom (UK), Canada, the Faroe Islands, Australia and Ireland (Pillay & Kutty, 2005). According to Forster (2006), the spectacular increase and large-scale success of salmon cage farming within these countries can be associated to a number of different interconnected factors, including:

Development of a replicable technological system that is low-cost for cage aquaculture farming of the salmon fish (i.e., the use of comparatively simple standardized floating cage culture systems for salmon grow-out); Access to long coastline with a wider continental shelf (Norway and Chile having a 1,800 km and 1,500 km long coastline, respectively); The Salmon fish is a very good fish species for cage culture farming (overall there are three different species, with straightforward hatchery rearing technology, they grow well in cages with rapid growth to market size and high fillet yield approximately 60% with highly acceptable meat);The market system is readily available with quality product development (including fresh fish supply year round with good perceived health benefits, numerous value added products, branded programs, generic marketing); Benefit of increased corporate investment, economies of scale, and consequent financial stability and regulatory compliance; Benefit from good national government support and regulatory environment (allocation of space and predictable permit process, practical regulatory framework, security of tenure, funded public and private sector research and development in support of the sector); and Importance placed on optimum salmon health and welfare, and consequent development of improved fish health management schemes (including optimum juvenile quality, water quality and physical conditions, successful vaccine development, and development of improved general fish welfare, handling, nutrition, feeds and stock management practices);

Nevertheless, world production of Atlantic salmon declined slightly in 2005 as a result of decreasing growth rate. For the other species reared in cages it is hard to separate data based on the type of environment where the culture practice takes place. FAO (2008) distinguished between freshwater, brackish and marine cage aquaculture production, however, the reporting by countries to FAO is not always consistent in distinguishing between culture in brackish water and marine environments, and therefore these two have been aggregated together. In freshwater environment, China dominates with a production exceeding 700, 000 tons equivalent to 68.4% of the overall reported freshwater cage aquaculture production, followed by Viet Nam 126, 000 tons or 12.2% and Indonesia 67, 700 tons or 6.6% (Halwart & Moehl, 2006). While the production in PR China is made of roughly 30 aquatic species, no specific production figures are available. However, the production in the other countries is comprise mostly of the clarias and the tilapias. The temperate region host a large proportion of marine and brackish water cage aquaculture systems with the most important species been the salmonids, yellowtails, perch-like fishes and rockfishes (Pillay & Kutty, 2005).

2.4.3 Perceived issues and challenges to cage culture development

Regardless of the above economic and technical achievements in the salmon cage aquaculture industry, the sector has been challenged with a number of issues during its development (Halwart & Moehl, 2006). Generally, these issues and challenges can be related to the use of open net cage-based aquaculture system and the consequent real or perceived impacts of such farming systems on the surrounding aquatic environment and the ecosystem, and they include: Increased nutrient loss from uneaten feed, faecal wastes and excreta from cage-cultured fish and their possible impacts (negative or positive) on water quality and the surrounding aquatic environment and ecosystem health (Mente et al., 2006; León, 2006); Increased risk of disease outbreak within cage cultured environment and the possible risk of diseases transfer to the natural fish populations (Blow & Leonard, 2007; Ferguson et al., 2007); High dependency on cage-cultured carnivorous fish species that rely heavily on fishery resources as feed inputs, including fishmeal, fish oil, and low-value “trash fish” species ((Halwart & Moehl, 2006); High dependency of some cage fish farmers for the collection of fish seeds from the wild and in particular of marine fish species for which hatchery development is new and production not currently enough to meet the demand (Asiedu et al., 2016); High risk of fish escapes from cages with possible consequences (negative or positive) on wild fish populations, with potential genetic, ecological and social impacts (Blow & Leonard, 2007); High potential risks of cage aquaculture practice (negative or positive) on other animal species, like predatory birds and mammals attracted to the fish within the cages

(Beveridge, 2004; Asare, 2013); Conflict with community concerns (in some countries) with respect to the use of shared public freshwater and coastal water bodies for culturing fish within cage-based farming systems that has the potential to displace fishermen and others, or perceived visual pollution, and the consequent need for increased consultation with all stakeholders (FAO, 2006); Increasing need for innovation and development of sufficient government policy and control measures regarding the development of the sector, including planning and environmental monitoring (Halwart & Moehl, 2006); and Increasing public concerns (in some countries) regarding the long- term environmental and ecological sustainability of the intensive cage aquaculture systems (Costa-Pierce, 2003; Tacon et al., 2006).

It is necessary to highlight here that fish farming (including the practice of cage aquaculture systems) has a number of important social, economic and environmental benefits, particularly increasing food security and poverty alleviation, increasing employment opportunities within rural communities, increasing seafood supply and availability, improving human nutrition and well-being, increasing foreign exchange earnings, improving waste water treatment or water reuse and crop irrigation opportunities, and improving nutrient recycling all of which need to be taken into consideration and weighed by importance in a balanced comparison of food production systems (Halwart & Moehl, 2006).

2.4.4 Diversity of cage types

Cage fish production developed from a humble origin and today a huge number of cage type and design are in use. However, there are four main types of cages. The fixed, floating, submersible and submerged cages. When net bags are supported by poles driven into the bottom of the aquatic environment in lake or rivers, such installation is been referred to as fixed cages (Beveridge, 2008). Fixed cages are mostly used in tropical regions such as the Philippines and are simple and inexpensive to construct. The challenge with fixed cages is their limited size and shape and their installation restricted to shallow waters with a suitable substrate (Pillay, 2005). Floating cages on the other hand are supported by a frame with buoyant collars and are the most widely used in cage fish farming today (Beveridge, 2004). Floating cages can be design in diverse ways to meet the growing needs of the fish farm industry (Pillay, 2005). They offer less challenge in meeting farmer needs when it comes to site selection requirements (Beveridge, 2008). The net or rigid bag submersible cage do not have a collar but have a frame and may depend on rigging to keep it in shape (Pillay, 2005). The advantage of submersible cages over the other designs is the absence of floating frames on the surface of the water (Pillay, 2004). Submerged cages are constructed of a wooden box with spaces between the slates to facilitate the movement of water and are positioned in the benthic part of the aquatic environment with stones to culture the common carp in flowing waters in South East Asia, particularly in countries like, Vietnam, Indonesia and the Philippines (Vass & Sachlan, 1957; Costa-Pierce & Effendi, 1988) and to rare lobsters in Vietnam (Tuan *et al*., 2000). The submerged net bag types are also used to culture fish in dams and lakes in the Union of the Soviet Socialist Republic (USSR) and China (Martyshev, 1993; Li**,** 1994). The question of all species readily adapting to culture in submersible or submerged cages remain unanswered.

Irrespective of the diversity of cage design and types that have being produced by cage manufacturers in recent times, the variety of cage type today are small compared to a decade ago (Beveridge, 2004). Cost has been the overriding variable in the design and type of cages to be manufactured on an industrial scale, leading to the uniformity of cages on the basis of shape, size and material (Pillay, 2005).

Cages are fairly less expensive and they are a convenient way to farm aquatic animals and have been used for a variety of other reasons connected to fish farming. For many years cages were used to hold and transport fish as baits for the tuna pole and line fishing industries (Ben Yami, 1978; Takeshima & Arimoto, 2000). Today the use of holding fish in cages has been surpassed by live-bait holding in boats and in countries like Japan for holding fish captured in traps until when ready for marketing (Beveridge, 2004). Additionally, cage fish have been used to monitor water quality release for the evaluation of eutrophication rates of the aquatic environment (Pillay, 2008). Cages have been used in research work that focus on the exclusion of environmental factors or as a substitute to replicate pond culture (Struve & Bayne, 1991).

Generally, cage farming focuses more on fish production to meet the global needs or demands for fish and fish product. Cages can be use in the rearing of the different life history stage of fish ranging from eggs, larvae, fry, and fingerlings and all the way to adult size (Pillay, 2008). Hatcheries based- tilapia cages originated in the Philippines and were quickly spreading in South East Asia. According to Little & Hulata (2000), less expensive cost and careful management of brood-stock and fish seed are the primary advantages for the use of cages over other system. The culture of the early life history stages of tilapia in cages is currently widespread in many countries. The application of cages in the culture of shellfish and finfish to market sizes has been also widespread globally (Beveridge, 2004). Similarly, to many types of fish farming activities, cage aquaculture can be considered on the grounds of feeding regime as costly and a large-scale aquaculture production system or either as semi-intensive or intensive aquaculture production (Pillay, 2005). In an extensive aquaculture production system, the cultured fish rely solely on food supply from the natural food coming from primary production by the planktonic organisms in the waters (Beveridge, 2004). In the semi-intensive systems supplementary feeds locally made by farmers are used to feed the fish in addition to the natural productivity of the waters while in intensive aquaculture system, the cultured organisms depend entirely on an external supply of food containing all the nutritional requirements for improved growth performance and survival of the cultured organism (Pillay, 2008). Lakes, dams in freshwater ecosystems are largely used for extensive cage fish farming as well as water bodies receiving waste discharge from sewage and domestic waste plants (Beveridge, 2004).

2.4.5 Extensive Cage Fish Farming

Different authors have suggested cage fish farming as an aquaculture practice that leads to fouling on the surrounding community. In extensive cage aquaculture systems, the area for colonization by fouling animals is extremely large. According to Huchette & Beveridge (2003), the culture of tilapia in an extensive cage culture system with fish production of 0.945kg fish m^{-2} per day in the surface water prove to be economically non profitable. Extensive cage fish farming is limited to waters with low salinity and is usually practiced in two environments, the dams and lakes (Shenoda & Naguib,2002) and streams and rivers into which sewage domestic waste have been discharged (Kabiria *et al*., 1999). Photosynthetic process that stimulates energy conversion in food chains within the aquatic ecosystem, besides waste feed system and system with increasing allochthomous materials rely on the existence of the required nutrients such as phosphorus and nitrogen molecules as well as solar energy and temperature needs of the cultured animal (Le Cren & Lowe-Mc Connel, 1980). Systems with increasing amount of phosphorus and nitrogen inputs are highly productive. Nevertheless, production is highly related to latitude, with high primary production levels in tropical areas followed by the temperature zone and the polar areas respectively (Beveridge, 2004). Water bodies in low latitude are characterized by an increasing amount of phosphorous and nitrogen loading and they are the best environments for extensive cage culture. Large scale extensive fish farming has been practiced largely in South East Asia (Beveridge, 1984a). Additionally feed inputs in an extensive cage culture system depends on whether the feeds are available and will be added when available rather than on the basis of ration (Pillay, 2005).

2.4.6 Intensive Cage Fish Farming

Intensive cage fish farming is mostly restricted to the culture of carnivorous animals of high economic value (Pillay, 2008). In low saline aquatic ecosystem, the salmon fish and catfish are cultured intensively, while in the waters of higher salinity, the yellow-tail, sea bass and milkfish are the main species cultured intensively (Beveridge, 2004). In Europe, North America, Singapore and Taiwan, intensive culture of omnivorous low valued tilapia and carps have been practiced. The main feed use in the culture of the yellow-tail, groupers and tuna is trash fish, while commercial feeds are readily available on the market for the culture of salmonids and the catfish (*Ictaturus Puntatus*) (Beveridge, 2004). Intensive cage fish farming systems cannot be practiced in the fast-flowing waters to avoid feed loss as a result of feed wastage by running waters (Pillay, 2004).

2.4.7 Monoculture and Polyculture systems

Monoculture and polyculture are the cultivation of one or several species in the same unit culture system. When one species is cultured in a single cage, the practice is been referred to as monoculture and when several species are cultured in a single cage the practice is known as polyculture (Pillay, 2005). Integrated fish farming is the incorporation of other agricultural practices such as rice cultivation in swamps and wetlands, poultry and piggery farming with fish farm practice. In practice monoculture is the rule for cage fish farming, while a polyculture system can be hardly sustainable or less economical in cage fish farming (Pillay, 2005). A good number of reasons may account for this. Fewer feeding niches are known to occur in cages compared to pens and ponds and for pens and ponds, natural feed inputs are available for confined bottom and plant feeding species, where the feed inputs are limited for planktonic feeding species (Pillay, 2008).

Research in cages with the carp for a polyculture system was conducted in Hungry with little or no success (Muller & Varadi, 1980). The Echinoderm (*Psammechinus miliaris*) has been cultured in floating nets of salmonid cages with some reasonable success, with the Echinoderm feeding on waste feed from the salmon fish with rapid growth performance during cold periods (Kelly *et al*., 1998). According to Lumbardi *et al*. (2001) various types of algae has been cultured in shellfish cages with the algae utilizing the waste from the shrimps and the shrimps benefiting from the shade provided by the algae. In the People's Republic of China, the culture of the silver carp and the bighead carp in floating cages has been practiced with production rates of 7.5 kg m^{-3} per year from extensive cage culture systems and 13.5 kg m^{-3} in semi-intensive well managed cages (FAO, 1983; Li, 1994). The advantage of rearing several high value species in intensive cage fish farm system has been viewed with mixed opinion and trial experiments has been conducted in Scotland to determine the possibility of culturing two predatory species together, the turbot (*Scopthalmus maximus*) and the salmonid resulting to little success (Pillay, 2008). Nevertheless, the culture of catfish (*Ictaturus puntatus*) and the rainbow trout (*On corhynechus mykiss*) yielded significant weight gain in the polyculture system than when reared in a monoculture system. (Beem *et al*., 1998). Even though no conclusion has been reached, the catfish possibly benefited from the polyculture system via the high food inputs. Excessive feeding activities of the tilapia are known to stimulate the feeding response of the catfish in a polyculture system of tilapia and catfish with enhance growth performance and survival as well as high yields of the catfish. Generally, not all advantages are food related.

Integrated cage fish farming, the incorporation of cage fish farming with other agriculture practices are more challenging to be practiced in cages than in pond fish farm practice (Beveridge, 2004). Experimental trials to integrate poultry and other livestock practice with cage fish farming has proved to be less successful and it has only been attempted in a small number of countries. In certain areas in South East Asia and the middle east, cage fish farming has been integrated in the control of multi- use of aquatic environment and in New Zealand and the United States of America (USA) trial experiments have been conducted to incorporate cage culture with irrigation and domestic waste water treatment systems for the enhancement and improvement of water use. Even though, the possibility of utilizing fish farm waste has been considered, trials to incorporate intensive cage fish farming with other activities in saline water ecosystem are still at the preliminary level

(Pillay, 2005). Research for the incorporation of cage fish farming with algae and echinoderm culture has been tried in North America and the Philippines. The farming of shellfish in waters with low salinity as well as in waters with high salinity has been experimented to deal with the problem of eutrophication. Carbon isotope studies have been conducted to evaluate under oligo-mesotrophic conditions in slow moving waters, suggesting that fish waste and uneaten fish feeds from cages harboring the sea bass (*Dicentrarchus labrax*) and sea bream (*Sparus aurata*) were consumed in reasonable quantities by the nearby mussels (*Mytilus galloprovincialis*). Waste water from industries has been used for fish farm activities in the incorporation of bio filtration with intensive coastal fish farming (Pillay, 2004).

Regardless of the few sustained success that has been made in the incorporation of cage fish farming with other agricultural practices, there is little proof in the change of opinion regarding the development of the cage fish farming sector (Pillay, 2008).

2.4.8 Cage Fish Farming and Algae Culture

Research trials of over one hundred and fifty species including shellfish and finfish are been conducted in cages. Some candidates that are not fit for domestication and rearing in small size cages are included in the list above. In cages, that are large enough, fast swimming species like tuna fish that have been found to quickly adapt to floating cages. Benthic dwelling animals such as the flat fish have been rared with little or no challenge in cages installed in slow moving waters with solid bottom attachment. Estuarine fish that camouflage in rocks and corals to capture their preys have shown little or no success when cultured in cages (Beveridge, 2004).

2.4.9 Cages and Global Aquaculture Production

The existing cultivation of farmed fish in floating net cages is a comparatively recent fish farm innovation technology, even though the history of cage use for keeping and moving fish for short distances can be traced back two centuries ago in the South East Asian region (Pillay, 2005). Cage culture in the marine environment started in Norway in the 1970s during the rapid development of the salmon fish industry (Beveridge, 2004). In the recent twenty years, cage farming has shown a tremendous increase and currently going through spontaneous changes as a response to pressure from the risen global needs for animal protein supply (Pillay, 2008). It has been suggested that fish consumption in developing countries is likely to increase by 57% from 62.7 million metric tons in 1977 to 98.6 million tons in 2020 (Delgado *et al*., 2003). Compared to consumption in the developed world, it will rise by 4% from 28.1 million metric tons in 1997 to 29.2 million metric tons in 2020, with the uncontrolled population increase in developing countries being the leading major reason for the difference.

2.5 Cage Fish Farming and its Impacts on the Environment

The essential water quality and ecological needs for aquatic animals often seen in the fish farm industry are problems associated with environmental pollution. On the basis of the type of aquaculture practice, the quality of water that is discharged from the fish farm is for the most part better than the water that flows from natural sources like rivers and streams (Beveridge, 2004). Aquaculture systems operate as effective means of agricultural and domestic waste recycling agent and inconsequence abates environmental contamination (Pillay, 2008). Matters of concern have been raised among fish farmers in some tropical regions, particularly in Africa regarding fish cages as a source of nitrogenous waste that augment plankton blooming with lethal effect resulting to fish kill (Pillay, 2008). However, this loss of fish can be avoided through proper feeding regime to avoid uneaten fish feed discharge in the aquatic environment and the implementation of best management practice.

Other concerns raised in respect of aquaculture having adverse effects on the environment has been the issue of fish farmers collecting eggs and larvae of cultured species from the wild, which was seen by fishermen as a possible cause for the reduction in their catches. However, there is little or no scientific evidence for such a claim as eggs and larvae collected from the wild form just a small proportion of those that could have died under natural conditions (Pillay, 2008).

Nevertheless, fish farmers at global level have developed technologies of producing fish seeds for aquaculture farms and are not relying so much on seed collection from the wild. Additionally, hatchery produced fish seeds have been used to supplement wild fish stock populations. Genetic manipulation and the establishment of exotic species for fish culture, has made the introduction of these exotic species in new ecosystem possible and with little or no adverse effect, bringing a reliable source of animal protein supply and meeting the recreational needs of the tourist industry (Pillay,2008a). However irresponsible introduction of these exotic species in new ecosystem may have adverse environmental and ecological effects on the native species. The practice therefore has not been encouraged by most governments and therefore has been limited by policies that discourage such practice (Pillay, 2008b). When technological advancement was paltry in cage aquaculture, the practice was being considered an environmental friendly activity. Currently a change in view has been developed in more recent times with the introductions of more advanced technologies in fish farm practices, coupled with the extensions of fish farm activities in the marine environment (Pillay, 2008). Global concerns with the consequences of irresponsible fish farm development associated with adverse environmental degradation has forced many governments to review their policies towards fish farm developments in their countries. Most governments today focus on a detailed environmental impact assessment as a requirement for the establishment of an aquaculture development program to ensure a secure and sustainable environment, while mitigating adverse environmental contamination (Pillay, 2008a).

Generally, fish farmers are often surprised when intensive fish farm practice is viewed on the same scale with other well established pollution generating activities that has an irreversible change on the ecosystem (Pillay, 2008b). Even in the absence of large-scale fish farm production, higher feed inputs may result to the release of nitrogenous waste coming from the breakdown of fish waste and uneaten feeds within the aquatic environment (Pillay, 2005). Another reason that is linked with conflict of fish farm practice and the environment is the extension of cage fish farming in the marine environment and the introduction of Shrimp farming in wetland area in tropical regions (Pillay, 2008). Irresponsible clearing of mangroves wetlands for fish farm practice has been observed in many tropical countries, not just for shrimp farming but also for harbor and road establishment, salt productions or drilling of oil and discharge of industrial waste (Munguti et al., 2014). Cage aquaculture in dams, reservoirs and coastal environments is associated with high stocking density and feed application with the resulting consequence of increasing nitrogenous waste release in the environment that requires high biochemical oxygen demand and increasing sedimentation (Pillay, 2008).

The concentration of cages and pens for fish cultures in dams and reservoirs may result to auto pollution and disease outbreak. Aquaculture practice has been in conflict with other associated use of coastal areas such as recreation, navigation and the beauty of the scenery view of the coastal environment thereby prompting government to come up with policies that regulate fish farm expansions in coastal areas (Pillay, 2008).

Sustainable fish farming should be one that does not create irreversible consequences to the aquatic ecosystem but limit the unavoidable change within natural fluctuations (Pillay, 2008b). Then, essential control system has to be introduced for a sensible use of the aquatic environment in the presence of effective and efficient policies as well as a controlled sustained measures based on scientific knowledge (Pillay, 2008a), in relation to possible development and the means to mitigate these impact on specific fish farm establishment and development.

Generally in practice, control measures for cage aquaculture practice are extended to control policies related to agriculture, animal husbandry, and industrial establishment to include fish farming though they may not be related. Even though fish farming is an old activity it is being characterized by a feeble scientific foundation with most research work focusing on production technology and the management of water quality variables within the fish farms establishment (Munguti et al., 2014) . Nevertheless, public concerns over environmental consequences of coastal fish farming have created the need for some research in Europe to determine the point source and composition of effluent release from fish farm sites and how they may influence the surrounding ecosystem. Extensive meetings and agreements on the effect of mangrove restoration has been done. Beside these meetings other ecosystem challenges associated with fish farm practices are for instance the introduction of exotic species for stock enhancement and the application of chemicals to improve fish production coupled with the alteration of water use patterns (Pillay, 2008).

2.5.1 Nature of environmental impacts

2.5.1.1 Conflict with other users

The composition and strength of ecosystem challenges associated with fish farm practice are related to the site and type of fish farm activities as well as the level of production technology involved. Currently most fish farm production come from inland fresh water and coastal marine fish farms in the intertidal zone. Even though essential agricultural lands may be considered ideal areas for fish pond construction such areas may not be available for fish farm practice causing fish farms to be established on wetlands which are normally considered as wastelands (Pillay, 2008; Dahlback & Gunnersson, 1981).

Since site selection for the establishment of fish farms has to do with access to surface or underground sources of water, wetlands are often seen as the most appropriate areas for the construction of fish ponds because of the high-water table and flood land areas. However, wetlands should not be seen as wastelands since they appear to have other significant uses. Even though they may not be used directly by human beings, they play a critical role in biodiversity conservation and ecosystem preservation (Munguti et al., 2014). Wetlands are counted among the most productive natural ecosystems and they are a source of nutrients for primary production to support life in marshy areas and the surrounding water bodies in which they drain. The significance of costal wetland areas as a nursery and feeding grounds for the early life history of marine species is important in considering their conflicting use with fish farm establishment.

2.5.1.2 Sedimentation and obstruction of water flow

In coastal shellfish culture and cage fish farming, sedimentation and the obstruction of coastal water flow are critical challenges to be taken into consideration during fish farm establishment (Dahlback & Gunnersson, 1981). The sediment may constitute and comprise of fine particles of organic matter or coarse sand that comes from the eroded water from the surrounding areas. The culture of mollusc within the intertidal zone is associated with sedimentation which for most of the time may lead to abandonment of culture beds and moving the beds towards the sea area (Dahlback & Gunnersson, 1981). Horizontal beds of bottom cultures do not for most of the time influence the patterns of water flows in traditional forms of bottom cultures. However, in the rack culture system where bags of oysters are placed on racks arranged in lines hundreds of meters long parallel to the tidal current, sediments may accumulate below and in between the culture racks (Dahlback & Gunnersson, 1981). In the "buochot" type of mussel fish farm system on poles installed in the seabed as a common practice in France (Pillay,1990), the poles act as barriers against water circulation when the mussel attain adult size and block the spaces between the poles leading to increasing sedimentation with the consequence of resuspension of the sediment during succeeding tidal flow.

Ottman & Sornin (1985) observed that, the poles will eventually submerge half their length as a result of sedimentation. Research in Sweden reveals that sedimentation rate in mussel fish farms can be thrice the observed distance away from the mussel farm. Besides the discharge of detritus that influence the patterns of water movements, biodeposits produced by bivalves as filter feeders may as well contribute to the rate of sedimentation (Dahlback & Gunnersson, 1981). However, these biodeposits make use of a considerable amount of oxygen in the process of oxidizing the organic matter they contain, eventually minimizing the dissolved oxygen concentration in the water column (Dahlback & Gunnersson, 1981). Normally, hydrogen sulphide (H_2S), a toxic substance is discharged in the environment as a result of this oxidization process.

Cage aquaculture system also adds a significant proportion of the detritus and sediments deposits which when not discharged or removed by currents may accumulate and become pollutants affecting both the environment and fish growth performance and survival (Dahlback & Gunnersson, 1981). Organic loading can promote hydrogen Sulphide (H_2S) release and decrease of the diversity of organism that occupy the benthic environment. Fish waste and uneaten fish feeds contributes ammonium- nitrogen and phosphate - phosphorous nutrients to the surrounding ecosystem thereby doubling the concentration level of these chemicals (Larsson, 1984). In fish ponds, concrete tanks and raceway with intensive culture practice characterized by increasing rates of stocking density, feed application and waste water movements may have a different mechanism to discharge detritus and organic deposits (Dahlback & Gunnersson, 1981). The waste water discharge from fish ponds, concrete tanks and raceways, constitute solids or soluble waste which may remain in suspension or settle on the sediments constituting mostly of organic carbon and nitrogen molecules. The waste that is soluble comes from metabolic process of the cultured fish or from solid waste via break down processes and leaching. The biological oxygen demand (BOD), as a measure of oxygen needed by micro-organism to breakdown organic substances is a critical measure for understanding the level of pollution strength in the aquatic environment. The influence of waste discharge from the fish farms on receiving aquatic ecosystem depends largely on local conditions (Pillay, 2008).

2.5.1.3 Hypernutrification and Eutrophication

Two major processes that originates from fish waste and uneaten fish feeds from cage fish farms are hypernutrification and eutrophication. Considerable measures of the concentration of soluble nutrients such as nitrogenous waste resulting from cage fish farms is terms hypernutrification and the consequence is an increase in phytoplankton biomass with adverse effects on dissolved oxygen known to result to the problem of eutrophication, In freshwater aquatic environments where eutrophication is commonly observed, dissolve inorganic phosphorous is known to be the most significant growth limiting nutrient, while soluble inorganic nitrogen is the most important limiting nutrient in the marine environment (Dugdale, 1967).

The composition of waste discharge from aquaculture farms is influenced significantly by the yearly production per unit volume of water and the retention coefficient of the water on the farm. Cleaning operations and feeding regimes are known to significantly influence the quality of waste water discharged from cage fish farms (Dahlback & Gunnersson, 1981). The consequences of waste water discharge in surrounding ecosystems are increase in total suspended solid and nutrient load coupled with decreasing dissolved oxygen (DO) concentration. Cage fish farm activities for instance feeding regimes, may result to the discharge of waste that cause both chemical and physical characteristic changes of the water. For example, an increasing concentration in the level of dissolved organic matter can lead to an increase in the number of planktons particularly diatoms and dinoflagellates.

In stream connected to cage fish farm establishment, the composition of plants in the stream can be largely filamentous algae and in situations where the vegetation constitutes macrophyte they are mainly covered with diatoms or single cell algae (Pillay, 2008). The species composition and growth performance of macrophyte is related to grain size and how homogeneous the sediment composition is known to be. In the marine environment, changes in the natural phytoplankton composition and macro-algae have been observed to occur in fish farms with vigorous flushing rates of water (Pillay, 2005).

In the absence of primary production stimulation, changes cannot be seen in the phytoplankton composition and the abundance of macrophytes and diatoms. According to Inone (1972), evidence of nutrient release from cage fish farms can stimulate primary production below fish farms levels in rivers and some fresh water ecosystem with little or no impact on the downstream fisheries that receive waste water discharge from the cage fish farms in a number of countries (Alabaster, 1982).

Nevertheless, the consequences of waste water discharge from fish farms are more observable on downstream ecosystem from pen and cage fish farms. Much research has been done on the ecological impacts on cage farming in European countries where cage culture of the salmonids is been a major industry than any other kind of aquaculture production system. The installation of cages and pens in open waters will reduce current velocity and enhance sedimentation. Edwards & Edelsten (1997) suggested that current velocity within a cage maybe half the velocity on the outside of the cage. According, to Inone (1972), net cages with dimensions of 20 by 20 by 6m with a mesh size of 50mm, stocked with yellow tail fish at densities of 1.6 kg m^{-3} will reduced velocity inside the cage by 35% of current velocity outside the cage. The main ecosystem challenge of cage aquaculture can be viewed in the context of eutrophication of the ecosystem in which the cages are installed. The levels of eutrophication are determined through the application of the mass balance models with limiting nutrients such as phosphorous and nitrogen. Diverse opinions characterized the view of phosphorus as a limiting nutrient in fresh water environments while nitrogen is been observed as a limiting nutrient in the marine environment (David et al., 2015). However, it is more appropriate to consider the two elements as limiting or co-limiting agents. According to Enell & Lof (1983), the release of nutrient from fish cages has been estimated to be in the range of 10-20 kg phosphorus (P) and 75-95 kg nitrogen (N) per ton of fish produced per year.

2.6 Overview of Carrying Capacity

Generally, Carrying Capacity (CC) of an environment, is the level of resource use by both human and animal that can be sustained over long-term period by the natural regenerative power of the environment. It is complementary to assimilative capacity, which is the ability of an ecosystem to maintain a healthy environment and accommodate waste (Fernandes *et al*., 2001), or environmental capacity, implying the ability of the environment to accommodate a particular activity without unacceptable impact (WHO, 1986). Carrying capacity of an aquatic environment from ecosystem point of view aims at attaining resource use sustainability without a dramatic change to the ecosystem services of the waters beyond resilience (David *et al*., 2015). Additionally, Eriksen *et al.* (2019) defined carrying capacity as “the potential highest production a species or population can attain given a set of available resources”.

Carrying capacity is a vital parameter for ecosystem-based resource management. It set the limits of aquaculture production given the evaluation of environmental resource availability and social acceptability of fish farm investment (Kapetsky *et al*., 2013), thus avoiding “unacceptable change” to both the created ecosystem, its social functions and structures. Evaluation of carrying capacity is one of the most significant instruments for technical assessment of not only the ecosystem sustainability of fish farming as it is not restricted to farm or investment issues alone, but can be applicable to environmental, physical and social dimensions. Although these general ideas of carrying capacity for fish farm establishment are based primarily on fish production, they have been further developed into an understandable four-category approach based on physical, production, ecological and social carrying capacities (Inglis *et al*., 2000; McKindsey *et al*., 2006). Although these accepted definitions were originally described specifically for bivalve aquaculture, they have also been applied to finfish cage culture systems (Byron & Costa-Pierce, 2013).

2.6.1 Physical carrying capacity

This involves a measure of the availability of an appropriate environment for the establishment of a fish farm facility, taking into consideration the physical characteristics of the environment. It involves the evaluation of the physical development characteristics of an aquatic environment in view of water depth, wind pattern, wave action and currents from which a site can be isolated for a given fish farm establishment (McKindsey *et al.,* 2006).

Physical carrying capacity encompass the whole aquatic environment with focus on isolating the overall area with the potential for aquaculture development. Inglis *et al*. (2000) and McKindsey *et al.* (2006) recognized that physical carrying capacity does not mean the stocking densities or production biomass, but rather the useful quantifiable potentials for fish farm development in a given aquatic environment. In terrestrial fish farm development, physical carrying capacity is the available area for pond construction with a sustainable supply of water.

2.6.2 Production carrying capacity

This constitutes the highest fish farm production at the farm scale and incase of bivalve's fish farming, it applies to the stocking biomass for optimal fish harvest. However, production biomass when estimated at production carrying capacity can be limited to minor segments within an aquatic ecosystem such that the total production biomass of the aquatic water body will not be in excess of the ecological carrying capacity, for instance, fish cage culture in a lake (McKindsey *et al.*, 2006). Evaluation of production carrying capacity relies heavily on production technology, production system and capital investment, with investment being referred to by Byron & Costa-Pierce (2013), as the economic capacity for a secured fish farm investment.

2.6.3 Ecological carrying capacity

This is associated with the extent of fish farm production that can be sustainably supported without dramatic alteration of ecosystem services and processes. Byron & Costa-Pierce (2013) discussed a number of parameters associated with this definition and the estimation of ecological carrying capacity, and suggested that bivalve fish farming for instance may have an impact on the ecosystem since bivalves are both consumers (of primary producers) and producers (through the recycling of nutrients and breakdown of organic matter) with the concomitant ecosystem impacts of both. When estimating ecological carrying capacity, Byron & Costa-Pierce (2013) caution should be taken when considering cause and effect and partitioning impacts in relation to bivalve culture and other practices in the ecosystem.

Alternatively, fish cage culture, for instance, uses ecosystem services for the breakdown of waste materials, dead organic substances, recycling of nutrients and the supply of oxygen, but at a given quantity of fish biomass, the system capacity becomes less efficient to recycle nutrients and supply oxygen, leading to oxygen depletion as a result of the addition of nutrients that stimulate an increase of primary production leading to plankton blooms that cause oxygen depletion resulting to the release of toxic substances that ignite eutrophication and pollution problems (David et al., 2015).

2.6.4 Social carrying capacity

Social carrying capacity is related to the quantity of fish farm production that can be obtained in the absence of adverse social effects. Byron *et al.* (2011) reported that the main focus for the estimation of social carrying capacity is to measure the value of stakeholders' involvement in a science-based effort to quantify the extent of fish farm investments in their local waters. The loss of ecosystem processes and services associated with fish farm development inhibit social services. According to Byron *et al.* (2011), the state at which alternative social services are compromised as a result of the magnitude and concentration of fish farms in a particular area is the social carrying capacity of the environment. Angel & Freeman (2019) related social carrying capacity to the concept of trade-offs among stakeholders with rights to a common property resource and reported to be the most difficult to measure, but the most critical from the management perspective. For instance, widespread opposition to fish farm establishment in a given locality will hinder the chances of its expansion.

Successful establishment and development of an aquaculture facilities have sometimes "clustered" around (Beveridge, 1984; Wells *et al*., 2008; Byron & Costa-Pierce, 2013), site selection and carrying capacity assessment of inland and coastal aquaculture, resource availability and personnel to some level, with due consideration of a range of factors including, the environment, closeness to markets and transportation connectivity. These parameters have been quite important in fish farm establishment (Beveridge, 2008), especially in Asia-Pacific region where the practice began and the area with the highest fish farm production (Beveridge, 2004). However, continuous growth is not always guaranteed, and in most areas site selection for fish farm establishment is irrelevant thus limiting production (Beveridge & Phillips, 1993). Any growth in fish farm production means an expansion of cultivated areas, a higher density of fish farm installations and a rising use of feeds, fertilizer and chemical inputs, as well as a significant use of land and water resources (Byron *et al*., 2011). Since fish farming is a resource-based activity competing for economic, social, physical and ecological resources with other industries, its establishment is likely to negatively impacts other industries like fisheries, agriculture and tourism (Inglis *et al*., 2000).

Also, the utilization of ecosystem services may as well result to consequences with both socio-cultural and socio-economic implications (Lovatelli & Holthus, 2008). As a result, it is important for the carrying capacity of these systems to be considered integral components for the establishment (Byron & Costa-Pierce, 2013) and site selection process for fish farm activities, as paramount for the adoption of good practices and sound environmental management to improve the sustainability of fish farm-based food production. Various Institutions have called for proper planning of human activities such as aquaculture to be undertaken in a rational manner that promotes sustainability (Byron & Costa-Pierce, 2013). Such rationale must have essential components that constitute science-based approaches for decision-making and ecosystem-based approaches for integrated management.

Globally, fish farming will need to enhance production significantly in the future to improve adequate animal protein supply for the increasing human population (Aguilar-Manjarrez, 1996; Duarte *et al*., 2009). Although most fish farming activities globally takes place in freshwater ecosystems (Aguilar-Manjarrez & Nath, 1998), the use of the continental shelf ecosystems for fish farming hold the potential to significantly increase fish production with increasing environmental pressures on ecosystem goods and services. The establishment of fish farming activities has in the past been based on a combination of local demand and agro-ecology, with global demand and deteriorating capture fishery having an increasing influence (Kapetsky *et al*., 2010). Foreign involvement for the enhancement of aquaculture growth have often been driven by short-term objectives and geo-political boundaries without given critical taught to other important parameters for successful aquaculture (Angel & Freeman, 2019), often leading to restricted development and sustainability.

2.6.5 Ecosystem approach to aquaculture as a framework for carrying capacity

In 2006, the Department of Aquaculture and Fisheries of the United Nations Food and Agriculture organization (FAO) highlighted the need to establish an ecosystem-based management approach to fish farming for effectiveness and efficiency of the FAO Code of Conduct for Responsible Fisheries (FAO, 1995). The FAO code of conduct suggested an ecosystem approach to aquaculture (EAA), which they said is a strategy for bringing together fish farm activities with the wider ecosystem processes with focus on sustainability, equitable distribution of resources and resilience of the interconnected social-ecological services (Soto *et al*., 2008; FAO, 2010). The strategy is directed by threefold principles, namely:

Principle 1: Aquaculture development and management must encompass the entire sequence of ecosystem processes and services, and should not compromise the sustained delivery of the services to the community.

Principle 2: Aquaculture activities must lead to economic and livelihood enhancement of communities in which the practice is taking place with equity for all parties involved in the practice.

Principle 3: Aquaculture should be developed in the context of other sectors, policies and goals.

It is recognized that defining, developing and adapting existing methods to estimate carrying capacity, or its limits to "optimal environmental change", are critical tasks to moving forward with an EAA. Alteration of management structure have to push towards more rigid measures to licensing in many countries, for instance, the EU, Canada, the Republic of Chile and the USA.

Nevertheless, only in a small number of countries (Ferreira *et al.,* 2008a) has the assessment of carrying capacity at system scale been given consideration on the basis of defining and quantifying the possible fish farm areas as a first step before local agreements for fish farm investment. The implementation of the EAA at various geographic regions necessitates the compromise of three objectives that comply with the EAA protocols: (i) environment; (ii) socio-economic; and (iii) governance, in addition to multi sectoral planning (FAO, 2010). These three objectives and their relative importance may differ between countries and across continents, making it difficult to single out a uniform standard of compliance with regards to limits and thresholds (Byron & Costa-Pierce, 2013).

The four divisions of carrying capacity, according to McKindsey *et al. (*2006), can be balanced in line with region and fish farm operations. Hence, the three main objectives of EAA can be tagged with the four categories of carrying capacity, with the social carrying capacity covering the socio-economic and governance objectives of the EAA.

However, the requirement for compromise of the three EAA objectives for long-term sustainability of fish farming must be kept in mind. McKindsey *et al.* (2006) suggested a hierarchical framework to evaluate the carrying capacity of a given ecosystem, and concluded that, stage one should include the evaluation of physical carrying capacity or site suitability depending on the natural conditions and the ecological requirements of the species and farming system, followed by estimating the production carrying capacity of the available area using models and still the application of models in the next stage to evaluate the ecological carrying capacity and determine the range of possible outcomes for production beginning from no production to maximum production level, as determined in the previous step (McKindsey *et al.*, 2006; Byron & Costa-Pierce, 2013).

The last stage will be to assess the diverse possibilities in respect of the outcomes from the previous steps and then make judgement on the level of optimum productivity leading to social carrying capacity. The first two stages of evaluating carrying capacity (physical and production carrying capacities) do not depend on social values, while both ecological and social carrying capacities do (Byron & Costa-Pierce, 2013). The last two stages need environmental parameters of importance to be defined by society before evaluating ecological and social carrying capacities.

Key features of fish farm successes, zoning, site selection and carrying capacity, including purpose, scope, scales, executing domain, data needs, needed resolution and outcome obtained, are considered in order to reveal how these factors connect to each other. This method is most necessary when new innovations are being accounted for or when there is no previous fish farm activity in the area (Byron & Costa-Pierce, 2013).

Possible site selection and zoning for fish farm are all innovative ideas that may follow a spatio-temporal sequence, starting with the estimation of possible opportunities and ending with the determination of physical carrying capacity. On the basis of spatial availability, possible opportunities have the widest range, with zoning being in the middle and physical carrying capacity been the narrowest (David et al., 2015).

Carrying capacity has to be accounted for at all levels of establishment and control. Temporal sequencing for the first three processes requires repetition as culture systems are established for new species or are reviewed for species already under culture. Additionally, carrying capacity has to be reviewed when altering the economic or infrastructure environment that makes previous unsuitable locations now attractive for investment. The beginning for decision on addressing the different units of carrying capacity will rely on the nature of the challenge and the stage at which it is being assessed. Clearly, some consideration for a standard format will be necessary especially for individuals who face such complexity for the first time. For example, in considering all four components of carrying capacity as being necessity, parallel or sequential processes needed to be considered (Byron & Costa-Pierce, 2013).

A wider range of planning evaluation is required to rely upon in the case of physical carrying capacity evaluation which at the start is given less consideration by current management protocols. This follows the reasoning that site selection must be based on an unbiased baseline that disrespects any management or otherwise control features of carrying capacity and any other factors, like competing land uses (McKindsey *et al.*, 2006). Furthermore, site-related considerations at a national or regional level may be the strategic establishment of sites concentrated or grouped into fish farm zones, or aqua parks, as has happened in many locations globally (Byron & Costa-Pierce, 2013). Once an area is deemed fit for fish farm establishment, a much more comprehensive work is required to tailor carrying capacity within its complete management structure, which may constitute complex production, ecological stability and social wellbeing (David et al., 2015). From this foundation, all sectors will function as complete, if calculations of carrying capacity can be in a way that either function to remove areas by limiting them, or acts to position the initial assessment against well-known regulatory standards (Byron & Costa-Pierce, 2013).

The progression and framework of this method, and its possible returns and outcomes, are critical in the process of carrying capacity evaluation. Some sectors of the methods will rely upon a scientific knowledge base, particularly from biological and environmental perspectives, while others may depend more on issues relating to livelihood enhancement and socioeconomic improvements (David et al., 2015). It should be recognized that, what may be seen to be a more objective scientific decision-making policy can be overshadowed by Governmental priorities. A good instance was the defeat made to Canada's prime minister for local distinctiveness (Cross, 2013). Evaluation and modelling of any of the unit sectors of carrying capacity can be considered as an independent policy weapon for carrying capacity, and it may be that significant decisions may not be necessarily focused on a single component. This may ensure choice or management strategies to minimize or wipe out the necessity for the evaluation of other carrying capacities.

Nevertheless, in many instances, more than one component of carrying capacity will be required to be investigated, and for a detailed, holistic policy frame work, all will be required. In such a scenario the relevance attached to a particular carrying capacity sector will change with location, based on national or regional needs, as well as ecological, cultural and social values (Byron & Costa-Pierce, 2013). Hence, it is not possible to single out a favorable method for the establishment of the four components of carrying capacities. In all multiple decision-making protocols, it is mostly the case for some factors to be assigned more relevance than others, perhaps in most cases, and this is well established in spatial analytical modelling. The same protocols are applicable in cases of more than one component carrying capacity evaluation, and a reason can be advance in situations that bring diverse components together, taking into consideration the alternating degrees of priorities assigned by national or local policies. For example, the western nations attached more significance to social values in management of resources, while eastern nations consider more of productivity maximization (McKindsey *et al.*, 2006).

Feed-based fish farming of cages in marine environments and or ponds fish farming in freshwater inland waters is mainly limited by physical capacity and wastewater management. In Southeast Asia and the People’s Republic of China, they focus more on production and physical carrying capacities, while in the EU and the USA national laws focus more on the negative consequences to humans for investments regarding natural resource exploitation (David et al., 2015).

Extensive fish farming, due to the feeding methods of the cultured fish normally occupies enormous areas of ecosystems on the basis of shoreline leases. The emerging factors concerning carrying capacity has been mostly (i) production related, such as the declining growth rate and harvest size of the Pacific oyster (*Crassostrea gigas)* in the Marennes-Oléron area of the French Republic in the mid-1990s, which was mainly associated with overstocking (Raillard & Ménesguen, 1994); or (ii) social values in western nations on the use of coastal areas for instance the geoduck industry in Puget Sound, (Cheney *et al.*, 2010), landscape values. The physical carrying capacity for extensive fish farm species has exceeded optimum capacity in many parts of Asia because of the rapid population growth in coastal marine ecosystems in collaboration with aquatic pollution. Fortunately, well planned shellfish aquaculture has revealed minimal consequences on the benthos (Fabi *et al*., 2009), even when extensive areas are cultivated (Zhang *et al*., 2009), bio-filtration for top-down management of eutrophication problems has been researched in many parts globally (Xiao *et al*., 2007), and it reveals that the occurrence of critical levels of shellfish culture in the People’s Republic of China has play significant role in the management of coastal eutrophication, possibly on a large scale (Sorgeloos, 2010).

Additionally, integrated multitrophic aquaculture (IMTA) has long been experimented in Asia, and is a vital farming system in the People’s Republic of China. At the moment, the focus is on co-cultivation across trophic levels, as represented by IMTA systems, which is growing in the EU and the USA, with interest in optimizing production in third world nations, while the western nations lay more emphasis on the reduction of emissions (David et al., 2015).There is connection between production optimization and emission reduction since for example low oxygen concentration of pond water is not only an outside ecological challenge but also an inside function of high fish death (McGinnity et al,. 2007).

The principles of site identification and carrying capacity can be cumbersome as ecosystem resources get beyond political barriers, for example, fish farming in the Mediterranean. The Mediterranean Sea is shared by 21 nations with diverse cultural, traditional, economic structures, social profiles and legislative policy frameworks, hence an approach focusing on multinational cooperation, exchange of information and harmonization of policy framework that sounds successful in the Mediterranean can be a model for other parts of the globe (Moffit & Cajas-Cano, 2014). Consequently, both FAO and the General Fisheries Commission for the Mediterranean have emphasized initiatives to help cooperation for improvements of fish farming and to facilitate round table meetings among Mediterranean States and stakeholders in respect of major issues, including site identification and carrying capacity evaluation (FAO, 2011).

Because there is little or no agreement among stakeholders and even between nations to set standard ecological fish farm policies, it is critical to leverage a compromising fish farm control policy framework. There is a diversity of approaches for this, one such is a clear definition on acceptable consequences by setting a standard and parameters to be applied for evaluating carrying capacity (IUCN, 2009). Another instrument is the application of factors associated with ecological integrity, for instance, primary production and sediment dissolved oxygen levels. Under all circumstances, the use of soft law instruments must be given consideration as a vital element of ecosystem standards equitability (Moffit & Cajas-Cano, 2014).

Finally, it is imperative to go beyond the site-by-site control procedures. Mandate on site identification can be done individually in reaction to the needs of tenure (McDaniels *et al.*, 2005). This process overlooks the fact that many of the important attributes include regional or sub-regional collective consequences goes beyond political barriers. The issues on scale and distribution of fish farm practices can be neither accounted for by aligning a local, site-by-site selection standard nor by a reactive approach but rather a proactive measure (Moffit & Cajas-Cano, 2014).The problem of setting standards has to be accounted for in a regional planning through scientifically established policies focusing on addressing the collective consequences connected to production, environment and social issues. Further regional planning must be considered to evaluate universal effects. Regional analysis of carrying capacities and its effects on a large scale may be costly (David et al., 2015). However, the application of prediction models and modelling is largely required to aid management decision. Models has the power to be applied at community, national and global level, and are excellent weapons for fish farm investment and control (Kapetsky & Nath, 1997). In evaluating fish farm opportunities, physical carrying capacity is the initial step towards planning for fish farm establishment. Global research on opportunities for inland freshwater aquaculture has been conducted for South America (Kapetsky & Nath, 1997) and Africa (Aguilar-Manjarrez & Nath, 1998). A regional assessment for the Caribbean applying the same methods was conducted by Kapetsky & Chakalall (1998).

2.7 Water quality variables for cage aquaculture production

For a sustainable cage aquaculture fish production, the quality of water is critical for all forms of operations. Water quality plays a critical role in fish growth, health and survival and water quality deterioration of any kind may amount to stress and cause health challenges with lethal consequences on production (Anusuya *et al*., 2017). Anusuya *et al.* (2017) reported an intricate interlude among various water quality parameters and suggested manipulation among them in diverse ways. A good aquatic environment is important for the growth and reproduction of fish, because the whole living functions of fish entirely rely on the quantity and quality of its environment (Bolorunduro & Abdullah, 1996).

Cage fish farming requires feed input, thus encouraging the addition of nitrogen and phosphorus-based nutrients to the water (Tacon & Forster, 2003) and base on the scale of feed input and what is consumed by the fish, may amount to eutrophication and pollution of the environment with devastating effect on the cultured fish. The primary physico-chemical variables to be considered in cage fish farming are water temperature, turbidity, salinity, pH, dissolved oxygen, ammonia, nitrates, nitrites, phosphates and chlorophyll-a concentration (Aura *et al*., 2018).

2.7.1 Water temperature

Fish are poikilothermic organisms, meaning their body temperature is relative to the temperature of their surroundings often 0.5 to 1^0C lower or higher than water temperature. The biochemical activities of fish are strongly related to water temperature such that increasing water temperature correspondingly leads to increasing biochemical activities of fish up to optimum levels within normal temperature (Aura *et al*., 2018) particularly for tropical fishes. For temperate and polar fishes, fish biochemical functions will proceed even at relatively lower temperatures, though at temperatures higher than 20^0C, they exhibit reduced activity and feed less (Anusuya *et al*., 2017).

Water temperature also controls the immunity of fish and can tolerate seasonal variation in temperature when they are in their natural ecosystem up to 0^oC in winter and a rise to 20-30°C depending on species in summer (Aura et al., 2018). Nevertheless, this change should not be spontaneous to avoid temperature shocks that may result to fish kill due to damage of the digestive, respiratory and circulatory systems of fish in a culture system. The degree of hotness or coldness of water is a critical variable for all forms of biochemical activities that govern living functions in an aquatic environment. When the temperature of the aquatic environment exceeds or become less than optimum temperature for fish growth, the biochemical activities that control fish growth and development are impaired, reducing growth and increasing mortality at high temperatures (Tacon & Forster, 2003).

The variation of temperature from 26.06^0C to 31.97^0C (Boyd, 1982) is good for fish culture in the tropics. Research has proven that, variation of temperature from 25^0C to 32^0C is suitable for warm water fish culture (Bolorunduro & Abdullah, 1996). According to Siti-Zahrah *et al*. (2008), high mortality rates were observed at cage fish farms in dams, in Tasik Kenyir, Malaysia. Mondal *et al*., (2010) reported average temperature of 21.38^0C in tilapia cage fish farms in Thailand. Zanatta *et al.* (2010) reported average temperature of 23.58°C in Jurumirim dam Brazil in tilapia cage fish farms. Maximum temperatures are observed in many aquatic ecosystems because of decreasing water levels, increasing air temperatures and decreasing humidity (Thirupathaiah *et al*., 2012).

Jiwyam (2012) reported average temperature of 26.71^{0}C in tilapia cage aquaculture in Thailand. According to Nyanti *et al.* (2012) water temperature decreases with increasing water depth in cage fish aquaculture in hydroelectric dams in Malaysia due to thermal stratification and lack of mixing in deep lakes and dams.

2.7.2 Water (pH)

The acidity of an aquatic ecosystem measured in terms of hydrogen ion [H^+] concentration is an important variable that controls cage fish farm productivity. The required pH for fish culture ranges from 6.5 to 8.5 (Castellucci & Kandel, 1974). Acidity (pH) values greater than 9.2 and lower than 4.8 can be lethal for cold water fish (brown and rainbow trout), while pH values higher than 10.8 and lower than 5.0 may cause mortality of cyprinids particularly the carps (Fall *et al*., 2012). Robert *et al.* (2009) suggests a pH range of 6.4 to 8.3 is ideal for fish growth. The limit of hydrogen ion [H^+] concentration for optimal functioning of life in an aquatic ecosystem is between 6.0 to 8.5 (Castellucci & Kandel, 1974). Records by Hepher & Pruginin (1981) show a value varying from 6.5 to 9.0 to be suitable for cage aquaculture practice. Generally, the hydrogen ion [H^+] concentration may decrease in cage aquaculture due to uneaten feeds and fish waste from cages (Beveridge, 1984; Pitta *et al*., 1999; Demir *et al*., 2001). Fall *et al*. (2012) reported ranges of hydrogen ion [H^+] concentration from 7.8 to 8.8 in Halali dam during the wet season, which was attributed to increased primary production and breakdown of organic matter that leads to increased nutrient load at high temperatures. Sewage pollution and waste from farmlands are also known to have contributed to the increase in hydrogen ion [H^+] concentration in aquatic ecosystems. Respiratory processes in the aquatic environment are known to contribute carbon dioxide to water and produce carbonic acid and increased hydrogen ion [H^+] concentration leading to acidification of the aquatic environment (Mallasen *et al*., 2012). Low hydrogen ion [H^+] concentration (Nyanti *et al*., 2012) is associated with increasing water depth because of breakdown of organic waste from plant materials and addition from feeds and fish waste from cages. Yee *et al*. (2012) recorded reduced pH value associated with low oxygen availability in water and increased biological oxygen demand because of decomposition of organic matter associated with excess feeds and fish waste. Lower pH values are generally associated with anabolic processes of aquatic life and breakdown of organic waste from fish feeds and fish waste. As a protective mechanism to mitigate low and high-water acidity fish normally secretes mucus on skin surface and the operculum as this condition may destroyed fish tissue particularly the gills (Mallasen *et al*., 2012).

2.7.3 Dissolved Oxygen (DO)

Oxygen gets into the aquatic environment directly from the atmosphere particularly where surface waters are mixing and as a by-product of primary production by planktonic organisms (Mallasen *et al*., 2012). Removal is accomplished through the breakdown of organic remains by bacteria during the catabolic processes in biochemical reactions (David et al., 2015). Dissolved oxygen plays a significant role in the growth and development of fish in cage culture systems (Anusuya *et al.*, 2017) and it indicates the biochemical activities occurring in the aquatic environment. According to Devi *et al.* (2017) dissolved oxygen concentration of 5 mgL^{-1} throughout the year will be suitable for fish cage aquaculture. Dissolved oxygen concentration in the aquatic environment may suggest the state of water quality in terms of bacteria load such that at low bacteria load level, Dissolved oxygen concentration is known to be high, while high bacteria load levels imply reduced Dissolved oxygen concentration (Amankwa *et al*., 2014) and the amount of Dissolved oxygen in water is critical for fish production and development as it controls the metabolic processes of fish and the breakdown of dead plants and animal materials as well as fish feed and fish wastes in cage culture systems (Mallasen *et al*., 2012)..

Increased quantity of Dissolved oxygen has been reported in the wet seasons because of monsoon winds promotion of water exchange rates. Low concentration of Dissolved oxygen in water is an initiator of eutrophication pollution as it facilitates anaerobic respiratory processes that released toxic chemicals in the water medium. Dissolved oxygen concentration is temperature dependent (Mallasen *et al*., 2012) as well as the level of primary productivity and stocking density in cage culture systems and it is as a result of anabolic processes by planktonic organism (Mallasen *et al*., 2012). Dissolved oxygen levels of 4.0 mgL^{-1} are optimal for the growth and development of warm water fishes. Increasing load of microorganisms (e.g nitrosomonas bacteria and nitrobacter) often deplete oxygen concentration at night due to the absence of photosynthetic processes and increase catabolic activities by yeast may cause the discharge of toxic chemicals in the culture medium (Mallasen *et al*., 2012). According to Nsonga (2014), Dissolved oxygen concentration above 5 mgL^{-1} is suitable for tropical fishes and low Dissolved oxygen concentration around cages is as a result of caged fish respiration and microbial activities (Cornel & Whoriskey, 1993). Swingle (1969); Neil & Bryan (1991) and Daniel *et al*. (2005) reported that Dissolved oxygen concentration less than 3.5 mg L^{-1} is unsuitable for fish culture. According to Boyd (1998) the optimal concentration of Dissolved oxygen in fish culture systems varies between 5 to 15 mg L^{-1}. Pollution consequences leading to fish mortality in cage aquaculture systems has been reported in reservoirs in the Philippines during the wet season when wind velocity is low causing low Dissolved oxygen concentration in the culture media (Yambot, 2000). Rani *et al.* (2004) recorded reduced Dissolved oxygen concentration in the rainy season because of the breakdown of dead plants and animal materials and reduced water movement. Dissolved oxygen requirements varies across fish species, cold water fish like the salmonids are more demanding in terms of Dissolved oxygen needs at most 8-10 mgL^{-1} for normal functioning, values lower than 3 mgL^{-1} can be unacceptable, while cyprinids are less demanding in terms of Dissolved oxygen requirements and perform well within concentrations of 6-8 mgL^{-1} and only shows reduced activity when concentrations fall below 2 mgL^{-1} (Mallasen *et al*., 2012).

2.7.4 Biological Oxygen Demand (BOD)

Biological oxygen demand is a significant variable in quantifying water quality deterioration state of an aquatic ecosystem. Biological oxygen demand on its own is not a stress to fish culture but indirectly becomes stressful through the utilization of dissolved oxygen thereby reducing its concentration in the culture environment (Anusuya *et al*., 2017) making the environment unsuitable for cage fish. Biological oxygen demand is the bacteria load that consumed dissolved oxygen in the culture environment. Increasing Biological oxygen demand concentration generates foul odour and results to a polluted culture environment that becomes a suitable environment for bacteria activity at high temperatures (Mallasen *et al*., 2012). It is directly connected to breakdown of nitrogenous wastes that are present in water linking high Biological oxygen demand level with eutrophication pollution that has inverse relation with dissolved oxygen (DO) concentration.

Biological oxygen demand estimates between 0.0 to 4.0 mgL^{-1} were reported in Hathanikheda dam in Bhopal (Namdev *et al*., 2011). Cornel & Whoriskey (1993) observed Biological oxygen demand variation between 3.2 and 6.8 mgL^{-1} in Halali dam. Biological oxygen demand concentration is mostly high in the deeper parts of the cage culture environment where the organic load is concentrated especially in the dry periods when temperatures are high corresponding to the increasing breakdown of organic matter (Banerjee *et al*., 1967).

2.7.5 Chemical Oxygen Demand (COD)

Chemical oxygen demand is the level of organic load in water mostly associated with the measure of chemical oxidant content in water. Chemical oxygen demand is the oxygen consumption potential by organic and inorganic chemicals through oxidation with a strong chemical oxidant (APHA, 1995). Chemical oxygen demand is extensively used to quantify the vulnerability to oxygen addition by highly reactive chemicals resident in water or originating from sewage coming from chemical plants (Chapman, 1996). Hence, Chemical oxygen demand is an essential variable for measuring the degree of pollution in an aquatic environment. Chemical oxygen demand is directly proportional to rising concentration of organic and inorganic chemicals (Boyd, 1981). Garg *et al.* (2010) observed Chemical oxygen demand variation from 3.60 to 17.40 mgL^{-1} in Ramsagar dam.

2.7.6 Alkalinity

Alkalinity is a measure of carbonates and bicarbonates concentration in an aquatic environment. When alkalinity is high the aquatic environment becomes more stable in terms of acidity or pH. On the other hand, bicarbonates serve as a reservoir to produce carbon dioxide for primary production ensuring adequate oxygen addition to the culture environment. The optimal concentration of total alkalinity in freshwater culture system is between 5-500 mgL^{-1} (Lawson, 1995). Boyd (1982) suggested 20 mgL^{-1} concentration of total alkalinity in fertilized ponds because fish production is directly proportional to total alkalinity. Bicarbonates are usually associated with changes in oxidation-reduction potentials and are used to quantify the degree of productivity and water quality status (Anusuya *et al*., 2017). Mallasen *et al.* (2012) reported total alkalinity variation between 90 to 160 mgL^{-1} in Halali dam with high nutrient load. The variation of total alkalinity in Indian dams from 40 to 240 mgL^{-1} (Sugunan, 2011) were recorded with a mean value of 156 ± 19.16 mgL^{-1} for *O. niloticus* cage culture. Lucas & Southgate (2012) suggested total alkalinity value of 20 mgL^{-1} in water is suitable for a tilapia cage culture system.

2.7.7 Hardness

Water hardness implies the ability of water to form lather with soap (Boyd, 1998) and it is controlled by the amount of alkaline earth metal (magnesium and calcium) salt concentration in addition to bicarbonates, carbonates, sulphates, chlorides and other negatively charged ions (Anusuya *et al.*, 2017). One unit of hardness is equivalent to 17 ppm of calcium carbonate, and soft water implies water with concentration of 0 to 75 ppm calcium carbonate with the least potential to neutralized positively charged ions. Hardness with concentration in the range of 75 to 150 ppm $CaCO_3$ is considered medium hardness and concentrations between 150 and 300 ppm as hard water (Boyd, 1990, 1998) while concentration in excess of 300ppm with the largest potential to neutralized acidic conditions is considered very hard water.

Hujare (2008) recorded increased total hardness in the wet season than the dry season, associating this condition to decreased water volume and rising evaporation. A 15 mgL^{-1} hardness is needed for normal growth and development of tropical fishes (Bouwer & Chaney, 1974; Sharma *et al*., 2020). Lucas & Southgate (2019) suggested hardness levels in excess of 50 mgL^{-1} is suitable for *O. niloticus* cage culture system.

2.7.8 Nitrite-N (NO_2^--N)

The oxidation of ammonia (NH_3) or ammonium ion (NH_4^+) releases nitrites (NO_2^-) as a bye-product in changing NH_3 or NH_4^+ into nitrates (NO_3^-). This process is facilitated by aerobic chemotrophic gram-negative bacteria (nitrosomonas bacteria) in the oxidation of toxic ammonia (NH_3) or ammonium ion (NH_4^+) into nitrite (NO_2^-), the oxidize state of nitrogen that cannot be taken up by plant cell and nitrobacter oxidized nitrite to nitrate (NO_3^-), the oxidize state of nitrogen that can be absorb by plant cell in fish cage culture system (Lucas & Southgate, 2019). The transformation is fast and therefore do not promote increasing concentration of nitrites in the system. Increasing concentration of nitrites can results to reduced activity of fish hemoglobin causing the brown blood disease (Jiwyam, 2012). Boyd (1982) reported 0.3 mgL^{-1} concentration of nitrites has been acceptable for freshwater fish pond culture systems. Other studies have recorded concentrations varying from 0.001 to 0.28 mgL^{-1} in cage aquaculture systems (Siti-zahrah *et al*., 2008; Eglal *et al*., 2009; Mondal *et al*., 2010; Jiwyam, 2012;).

Nyanti *et al.* (2012) observed that the amount of nitrites concentration at cage sites were greater than the control because of nitrogenous waste from cages and uneaten fish feeds. It has been suggested that high pH levels, decreasing concentration of dissolved oxygen as well as increasing the concentration of ammonia are all associated with the toxicity of nitrogen (Eglal *et al*., 2009).

2.7.9 Nitrates-N (NO_3^--N)

Nitrates are a product of aerobic respiration by nitrosomonas bacteria from nitrites (NO_2^-) as an intermediary in the change of NH_3 or NH_4^+ through the oxidation process. Nitrates are the form of nitrogen consumed directly by autotrophic microbes (Furnas, 1992) and the component not utilized is release as free nitrogen by anaerobic bacteria. According to Boyd (1982), the acceptable concentration of nitrates in fish farm culture systems is from 0.2 to 10 mgL^{-1}. Sewage contamination often complement nitrates to surface waters. Increasing concentration of nitrates in domestic water is unhealthy (Imbaya, 2007) and the highest concentration level in water for human consumption was reported as 10 mgL^{-1} (Self & Waskom, 2008). Erosion from agricultural lands influence nitrates concentration to a large extent in the surrounding aquatic environment because of leaching of manure from farm lands (Karigar & Rao, 2011).

2.7.10 Ammonia-N (NH_3 -N)

Ammonia is the main nitrogenous waste discharged by fish through catabolic processes and release via the fish gills (Nyanti *et al.*, 2012). Its concentration often increases at cage culture sites because of waste discharge by fish and from uneaten fish feeds (Nyanti *et al.*, 2012). The release of ammonia in the aquatic environment strongly affects the concentration of dissolved oxygen as 4.6 mgL^{-1} is required to convert 1 mgL^{-1} of ammonia to nitrite. According to Boyd (2001) concentrations of 3 to 4 mgL^{-1} are dangerous for warm water fishes. Nyanti *et al*. (2012) reported concentration in excess of 0.2 mgL^{-1} unsuitable for cage aquaculture systems. Acceptable concentrations for inland aquaculture should be lower than 0.05 mgL^{-1} (Lawson, 1995). Nyanti *et al.* (2012) reported that concentrations below 1 mgL^{-1} are suitable for pond fish culture systems. Boyd (2001) recorded 0.1 mgL^{-1} as suitable for fish culture systems and that concentration of 0.02 mgL^{-1} is needed to optimize the health of tropical fishes. Lucas & Southgate (2019) reported concentrations lower than 1 mgL^{-1} are acceptable for *O. niloticus* cage culture system. Other studies reveal that concentrations varying between 0.01 to 1.15 mgL^{-1} are desirable for caged fish aquaculture systems (Eglal *et al*., 2009; Zanattha *et al*., 2010; Mallasen *et al*., 2012). Karnatak & Kumar (2014) reported that high stocking densities combined with high feeding rates usually result to decreasing dissolved oxygen concentration and increased ammonia concentration around fish cages particularly when there is reduced water mixing around fish cages. Ammonia toxicity in water is been influenced by temperature, pH and dissolved oxygen concentrations. Reduced dissolved oxygen concentration renders ammonia more toxic (Eglal *et al*., 2009). Water quality monitoring demand the quantification of total ammonia concentration. To validate the capacity of toxicity of these measured concentrations, it is relevant to measure the nonreactive ammonia (NH_3) available from the measured total ammonia (NH_4^++NH_3). The estimation of the non-reactive ammonia is as shown in equation (1) (Eglal *et al*., 2009);

$$(NH3) = \frac{(NH4 + NH3)}{10\ (10.07 - 0.33T - pH) + 1} \dots\dots\dots\dots\dots\dots\dots\dots (1)$$

2.7.11 Phosphorus-P (PO_4^{4-} --P)

Phosphorus is a limiting nutrient in fresh water aquatic environment and it plays a critical role in maintaining lakes and reservoir fertility. It is seen as one of the main water quality variables released from cage fish farms with adverse effects on the lake ecosystem (Jones & Lee, 1982; Ketola, 1982; Kelly, 1992; Guo & Li, 2003). Increasing phosphorus load in the aquatic environment will leads to eutrophication pollution with resulting fish kills in cage culture (Mawundu et al., 2023). The main channel through which phosphorus enters into the aquatic ecosystem from cage aquaculture farms is via the uneatened fish feed and fish waste (Garvine *et al*., 1995). A high concentration of fish cages in a given area with a poor feeding regime has the potential to contribute phosphorus in excess of the phosphorus assimilation capacity of the area with adverse effect on water quality for the culture environment (Mallasen *et al*., 2012). Labile phosphorus can be generated from decomposed solid waste (Kelly, 1992). According to Boyd (1998), the threshold level of phosphorus in the aquatic environment vary from 0.005 mgL^{-1} to 0.02 mgL^{-1}. Phosphorus is critical in the course of primary production as a limiting nutrient in fresh water ecosystem (Barik *et al.*, 2001). It was reported by Santos *et al.* (2012) that, the optimum concentration of phosphorus for *O.niloticus* culture is 0.025 mgL^{-1}. The WHO standard of phosphorus concentration in drinking water is 2.5 mgL^{-1} (Amankwaah *et al*., 2014)

2.7.12 Sulphates (SO_4^{4-})

Sulphates are a part of the total dissolved solids that contribute salts with alkali earth metals such as sodium, potassium, magnesium and other cations. Sulphates are not toxic in the group of heavy metals, herbicides and other toxic anthropogenic materials, but are common salts essential for aquatic life processes at some restricted quantities. Sulphates are quickly diluted in the aquatic environment and they do not bio accumulate. Sulphate concentration of 5 mgL^{-1} to 100 mgL^{-1} are optimal for aquaculture practice in fresh water aquatic environment (Boyd, 1998). It has been reported that sulphate concentration varies from 30 mgL^{-1} to 150 mgL^{-1} in streams without significant anthropogenic contribution in the north and central regions of Illonois (IDNR, 2009). Sulphates occurs widely in nature and are present in natural aquatic ecosystem in levels that range from a few to thousands of milligram per litre (APHA, 2012).

2.7.13 Total Dissolved Solids (TDS)

Total Dissolved Solid (TDS) are solid materials that are present in their dissolved states in the water column. These solid materials constitute both organic and inorganic salts and other dissolved materials in the aquatic environment. According to Garg *et al*. (2010), total dissolved solids values that ranged from 166.37 mgL^{-1} to 239 mgL^{-1} were observed in Ramsagar reservoir in Mahya Pradesh. Sawant & Chavan (2013) reported maximum levels of total dissolved solids of 172.66 mgL^{-1} in the dry season because of loss of water as a result of evaporation and high levels of salt contents in the aquatic environment.

2.7.14 Total Suspended solids (TSS)

Total Suspended Solids (TSS) as a water quality variable is a sign reflecting the quantity of erosion that has taken place in the nearby upstream environment. This water quality variable is the most important quantity as it reflects the most appropriate measure of control in aquatic environments. According to Yi *et al.* (2004), total suspended solid levels of 87.2 mgL^{-1}, 125.8 mgL^{-1} and 86 mgL^{-1} were recorded in the upstream, middle stream and downstream respectively of the Mekong River in Vietnam.

A high concentration of total suspended solids will obstructs light from reaching the water column thereby inhibiting the process of photosynthesis by phytoplankton and macrophytes. It has been reported that, high levels of total suspended solids in cage culture environments could be associated with fish waste and uneaten fish feed (Boyd, 2004).

2.8 Overview of Nile tilapia (*O. niloticus*) cage aquaculture system in the great lakes

The Nile tilapia cage aquaculture has been practiced in the great African lakes (Volta, Malawi, Victoria, Kariba and Kivu) (Halwart & Moehl, 2006). The lake Volta (one of the largest man-made lakes in Africa) hosts the two largest commercial cage fish farms companies in Ghana (Crystal Lake Fish Ltd. and Tropo Farms Ltd) (Kassam, 2014).These farms were established in the late 1990s in Asuogyaman district in the eastern part of Ghana and they culture indigenous tilapia (*O. niloticus*) in ponds and concrete tanks (breeding and juvenile rearing) and transfer them to cages where they are cultured to market size (Blow & Leonard, 2007). The Crystal Lake Fish Ltd farm has twenty four (24) circular eight (8) metre diameter tanks for hatchery production and nursing. When fingerlings attain the weight of 5 to 8 grams they are moved to cages (32 meter diameter and 5 meters deep), situated 1km offshore in 25 metre deep water (Rurangwa et al., 2015). Stocking density is approximately 100,000 fish per cage or 0.5 to 1.0 kgm^{-3} (Asase, 2013). The fish are fed with powdered feed during the first two months until they reach 40-50 grams and are then transferred to another cage at a density of 50,000-60,000 fish per cage for a period of three months to reach market size at a weight of 250 grams (Asiedu et al., 2016). The production circle is five months and annual production in 2006 was approximately 340 tonnes for the Crystal Lake fish Ltd

(Halwart & Moehl, 2006). The Tropo Farm Ltd practiced pond farming for 6 years before venturing into cage culture in 2005 on Lake Volta near the Akosombo dam. The current annual production of cages owned by the Tropo Farms Ltd is 10 tonnes per annum and they sell fresh fish at farm gate to the Ghanaian market (Asiedu et al., 2016). Both fish farms produce their own fry. However, getting good quality feeds is a major problem for the farms. Locally manufactured feeds are not available and feeds have to be imported from Europe. The Tropo Farm Ltd reported feed conversation ratio of 1.7 to 2.2 (Halwart & Moehl, 2006; Asiedu et al., 2016). There has been no serious reports of diseases outbreak though external bacterial infection (columnaris) and fish lice (Argulus) has been reported (Halwart & Moehl, 2006; Asare, 2013). Approximately 10% of Ghana's population is involved in the fishing industry and the production cost in the cage culture sector is roughly US$ 1per kg of fish. With quality feeds and improved economics of scale, tilapia cage culture can contribute significantly towards economic growth (Asiedu et al., 2016).

In Kenya commercial cage aquaculture was introduced in 2005 in Lake Victoria. A pilot cage site was first established in the 1980s. The existing fish cages in Kenya are for tilapia cage aquaculture production operated by the Orico Farm Ltd at Anyanga in the Kadimo bay Lake Victoria, Kenya (Orina et al., 2018). The Nile tilapia is not indigenous to Kenya but is allowed for cage culture in Lake Victoria as it was established in Lake Victoria in the 1970s and has flourished since then (Aura et al., 2018). There has been no attempts to introduce the genetically improved farmed tilapia (GIFT) strain in Lake Victoria. Because of the slow growth rate of the indigenous tilapia strain, selective breeding programmes are ongoing aiming to improve the growth performance of the local strains under culture conditions. The current cages are small size (4 m^{-3}), and farming is done on a commercial scale in hapa-type wooden-frame cages installed in reservoir areas and irrigation channels on Orico's large new arable farm established in Anyanga (Quagrainie et al., 2007). Currently there are 30 such cages on the Orico farm Ltd. with production nets made locally in Kenya. The stocking density at harvest is expected to be around 200 kgm^{-3} (Owour et al., 2019). Tilapia fry are reared on Orico Farms hatcheries and juveniles are cultured in cages own by the Orico farm Ltd. Quality Feed supply is one of the major constrain for cage culture commercialization in Lake Victoria, Kenya. Raw materials for fish feed production are available on the local market at affordable prices (Radull, 2005; Opiyo et al., 2018) but technical knowhow remain a challenge for feed extrusion. Orico fish farm Ltd is planning to own an extruder machine to mitigate the challenge. Feed cost is at the moment approximately ksh35, 000 ton^{-1} in Kenya for tilapia cage culture (Njiru et al., 2018). There has been no report of disease outbreak associated with cage aquaculture in Lake Victoria with adverse impact on the sector. Recently cage aquaculture has been a source of healthy animal protein supply for local communities in Kenya. A reasonable number of subsistence-level fish farmers have grown into small-scale commercial fish farmers (Njiru et al., 2004), with Some commercial farmers aiming to produce for both local and international markets; thus in the near future, aquaculture will likely contribute significantly to both food security and gross domestic product (GDP) in Kenya (Aura et al., 2017). Production costs is below US$1 per kg of fish for commercial tilapia farms in Kenya.

However, the existing small-scale cage aquaculture farming coupled with the poor feed quality has resulted to increasing cost of production. The wild captured tilapia and Nile perch (*Lates niloticus*) are available at affordable prices on the local market (Njiru et al., 2018). Nevertheless, this supply is decreasing due to overfishing and prices are increasing rapidly. At the moment cage aquaculture is aiming to produce fresh and frozen fish fillets for the local market. Cage aquaculture currently employs less than 10% of the Kenyan population along the fish value chain (Orina et al., 2018; Owour et al., 2019). Lake Victoria and Lake Turkana offers great potential for cage aquaculture as water quality in both lakes is good and water temperatures are within optimal threshold for tilapia culture throughout the year (Aura et al., 2018). However, Kenya's eastern part of Lake Victoria is comparatively shallow and accessible while Lake Turkana is somehow remote (Opiyo et al., 2018). These factors are critical in the development of cage aquaculture.

Nevertheless, it is a requirement for a detailed EIAs to be conducted before any cage aquaculture investment is allowed in Kenya (Aura et al., 2017. The lakes have significant wild captured fisheries that are community owned and harvested, and as the case with Uganda, there is some conflict to the idea of introducing cage aquaculture probably because this activity is either not known or not well understood by the indigenous people (Halwart & Moehl, 2006). This situation is however likely to change in the near future in Kenya. The aquaculture industry in Kenya is managed by the Department of Fisheries under the Ministry of Agriculture and Rural Development (Aura et al., 2018). This department is responsible for the administration and development of fisheries and aquaculture policies, enforcement of fisheries regulations including licensing, collection and reporting of fishery statistics data, market surveys, fish quality assurance and control of import and export of fish and fishery products (FAO, 2004; Halwart & Moehl, 2006). Aquaculture training institutions are available in Kenya on an occasional course basis.

The Department of Fisheries, has an MOU with the University of Eldoret that undertakes aquaculture extension training programmes. The Fisheries Department at the University of Eldoret has established an aquaculture facility that is been used for training, research, and extension services in the region (FAO, 2004; Owour et al., 2019). However, this facility basically focus on pond culture systems and the authors do not have direct knowledge on cage aquaculture training (Orina et al., 2018). There are several NGOs involved in aquaculture development programmes in Kenya, though none is specifically promoting cage aquaculture. The United States Agency for International Development (USAID) has been active in rural aquaculture development since the 1990s (Halwart & Moehl, 2006).

In Lake Malawi, the Maldeco Ltd, the oldest and most well established fish and fish processing company went into cage aquaculture in 2004 (Phiri et al., 2018). The Maldeco Ltd is the only cage aquaculture investment in Malawi (Halwart & Moehl, 2006). It farmed *Oreochromis shiranus* (locally known as “chambo”) in ponds (for breeding and juveniles rearing) and transferring them to cages (for rearing from grow-out to market size). Annual cage fish production is approximately 100 tonnes of whole fish (Halwart & Moehl, 2006; Nagoli, 2020). However, Maldeco Ltd is planning to increase production around 3,000 tonnes per annum in the future. It processes the fish on site near Mangochi and markets it locally as frozen whole fish and fish fillets. *Oreochromis shiranus*, *O. karongae* and red-belly tilapia (*Tilapia rendalli*) are indigenous in Lake Malawi (Kaunda et al., 2003). However, *O.niloticus* is not indigenous in Lake Malawi and the existing fishery policy in Malawi prohibits it introduction as well as other exotic species (Gondwe et al., 2011). Research for appropriate indigenous species for cage fish farming is ongoing at the Malawi National Aquaculture Centre and has been supported by various projects. The genetic advancement of indigenous species is also being researched. Selective breeding of *O. shiranus* and *T. rendalli* regarding their genetic integrity is ongoing at Malawi National Aquaculture Centre (Chimatiro & Chirwa, 2005).

The Maldeco Ltd. has square steel cages that are 6 meter deep and sourced from Europe. The cage location is approximately 200 meter offshore in deep waters, with reduced current velocity created by the beginning of water flow from the lake into the Shire River (Seymour, 2001). Cage fish production nets are nylon and are imported from Europe. Currently, Maldeco Ltd. has one cage site containing 10 cages. Juvenile tilapias are transferred from ponds and reared up to 300 g or more to sizes on demand for markets in Africa (Nagoli, 2020). Maldeco Ltd. targets to produce about 3, 000 tonnes per annum from both ponds and cages. Demand for farmed fish in Malawi is highly skewed in favour of the upland areas away from the lakes and in the urban centres (Chimatiro & Chirwa, 2005). Maldeco Ltd. breeds its own fry in earthen ponds at a site about 13 km from the cage location. Obtaining high quality locally produced feeds is the most serious challenge for commercial cage farming in Malawi. No disease outbreak has been reported in cage aquaculture in Lake Malawi. Cage aquaculture in Lake Malawi contribute significantly towards food security by increasing access to food and improving household capacity to afford food (Jamu & Chimatiro, 2004). Fisheries resources accounts for 4% of Malawi's gross domestic product (GDP) (Gondwe et al., 2011). Fish production from the aquaculture sector contributes approximately 2% of Malawi's fish production (Chimatiro & Chirwa, 2005). Cage aquaculture production cost is less than US$1 per kg of whole tilapia fish for commercial farms in Malawi. Nevertheless, feed quality challenge, low financial inputs and the cost for research and development associated with the production of new tilapia strains for cage culture all contributes to the increasing cost of production (Halwart & Moehl, 2006; Phiri et al., 2018).

In Lake Victoria, Uganda, cage aquaculture began recently in the early 2006 and is being encouraged by the state department responsible for fisheries management as an important development sector (Ndanga et al., 2013). The reason for this is due to the fact that revenues from the already overfished wild capture fishery in Lake Victoria, Uganda are the main source of foreign exchange for the Ugandan government and it is believed that cage fish aquaculture will complement these revenues (Halwart & Moehl, 2006). At the moment there are three phases of pilot-scale cage sites on Lake Victoria, in the Entebbe and Jinja areas. In Uganda, the Son Fish Farm Ltd, United Fish Packers Ltd form part of the three-year old USAID-funded fish farm development project. Cage performance results have not yet been reported in Uganda (Munguti et al., 2014). The Nile tilapia (*O. niloticus)* is indigenous in many parts of Uganda, even though introduction into Lake Victoria was done in the 1970s and has flourished since then (Nagoli, 2020). No introduction of exotic species has been encourage in Lake Victoria on the Ugandan side. Research is ongoing on selective breeding in Uganda aiming to improve the growth performance of the local strains of *O. niloticus* under cage culture farming conditions (Halwart & Moehl, 2006; Owour et al., 2019). Although existing data suggest growth rates to be satisfactory, the introduction of the genetically improved farm tilapia (GIFT) strains from foreign countries is being given consideration as the Uganda government look forward to fast tracking aquaculture development (Halwart & Moehl, 2006; Opiyo et al., 2018). The pilot-phase of cage aquaculture sites in Uganda have small intensively stocked cages that are approximately 5 m^3 in size (Halwart & Moehl, 2006; Ndanga et al., 2013). There are about 15 such cage sites in Uganda at the moment. The sites are all inshore in shallow waters (<5 m deep) of Lake Victoria. The cages are locally fabricated with metal frames and wooden walkways (Nagoli, 2020). Production nets are nylon made and are produce locally in Uganda. Predator nets are being used as a precautionary measure, though the predation risk has not been reported. The fish are being grown to an export-oriented market size of 700 g and are been processed for export in Uganda's 17 EU-approved fish plants (Halwart & Moehl, 2006; Njiru et al., 2018). Stocking densities are 200 fish per m^3 in experimental cages. Stocking density at harvest is approximately 100 kgm^{-3}. Tilapia fry are produced by a state owned hatchery at Kajjansi (near Kampala) and by Son Fish Farm Ltd commercial hatchery in Jinja (Ndanga et al., 2013; Munguti et al., 2014). Obtaining good quality locally produced feed is the major challenge for large-scale cage aquaculture development in Uganda (Halwart & Moehl, 2006; Orina et al., 2018). The raw materials for fish feed production are available locally at reasonable prices but the problem remain with the availability of equipment and technical knowhow for extrusion. There has been no report on diseases outbreak on cage fish farms in Uganda. Production costs is less than US$1 per kg of whole fish for a commercial tilapia farm in Uganda though this has not been reported (Aura et al., 2018).

In Lake Kariba in Zambia there are three small cage aquaculture farms in the Siavonga area that were introduced in the 1990s and none of these cage sites produces in excess of 10 tonnes per annum of whole fish (Blow & Leonard, 2007). All the cage farms reared *O. niloticus* and they produce their own fry and juveniles for stocking. *O. niloticus* is not indigenous in Zambia, though it was introduced in the 1980s for cage aquaculture along the banks of the Zambezi River (Kassam, 2014). No introductions of exotic species have been done since then and there is likely high level inbreeding among the farmed strains Opiyo et al., 2018). However, the introduction of exotic species is being given consideration by the Zambian government to enhance fish production. The size of cages on all the three farms are approximately $40m^3$, with wooden walkways frames. Production nets are locally fabricated with nylon and are imported from Zimbabwe. There are no predator nets in use. The three cage sites are located in shallow waters (<5 m deep) inshore areas and are close enough to land to have walkways out of the cage sites (Asiedu et al., 2016). The total number of cages is around 30 and Juvenile tilapia are transferred to the cages from earthen ponds, where they are grown to market size of approximately 350 g. Stocking density at harvest is around 20 kgm^{-3}. According to Maguswi (2003) there are four large-scale cage aquaculture farms practicing cage farming on Lake Kariba. They used 44 cages of dimensions 6 m x 6 m x 6 m (216 m^3) and 10 pens to grow *O. niloticus* and used pelleted feeds (Gondwe et al., 2011). Mean production for larger cages (216 m^3) is 3.5 tonnes per production cycle (Maguswi, 2003). The three cage farms each produce their own fry. A reasonably good quality locally produced extruded feed is available in Zambia but is expensive as it cost over US\$400ton^{-1} and not all the cage farmers can afford that amount. Tiger Animal Feeds is the largest specialized animal feed producer in Zambia (Maguswi, 2003). While poultry, pig and dairy feeds constitute the bulk of its production, the company is also involved in formulating and making fish and crocodile feeds. The company benefits from highly qualified staff, feed-mill equipment and has an agreements with a European company for fish feed production (Rurangwa et al., 2015). The production level vary with demand, with poultry feeds topping the list. The company has focused on feed formulation for various feeds to ensure constant product quality and consistency. All feeds are formulated with 95 % of high quality and laboratory-checks of local raw ingredients (i.e. wheat flour, maize meal, cooking oil) (Bentley & Bentley, 2005). No disease outbreak has been reported on cage aquaculture farms in Zambia. Fish production is an important source of national income and contributes immensely toward poverty alleviation, employment creation, income generation and food security (Halwart & Moehl, 2006). It is estimated that up to 55% of the national average protein intake in Zambia comes from fish and fish products (Bentley & Bentley, 2005). The contribution of fish to gross domestic product (GDP) in Zambia is estimated at 3.8% (Halwart & Moehl, 2006). This estimate is based largely on the contribution from capture fisheries, because production from the aquaculture sector is not regularly reported (Maguswi, 2003). Production costs is less than US$1 per kg of whole fish for a commercial tilapia cage farms in Zambia (Maguswi, 2003; Halwart & Moehl, 2006). However the relatively high cost of feed, as well as low income earnings of cage fish farmers makes profitability marginal. The three existing cage farms sell their fish at the farm gate in fresh form into the Zambia market with supply outlets in the urban areas (Maguswi, 2003). The demand for fish and prices are very strong in Zambia. Lake Kariba is a 5,000 km^2 freshwater hydroelectric dam-lake fed by the Zambezi River (Maguswi, 2003; Halwart & Moehl, 2006). Water quality of the dam is good for cage aquaculture, although a three-month colder season (June to August) limits fish growth. It is a requirement for a detailed EIA before any cage farm investment is allowed in Zambia (Halwart & Moehl, 2006; Blow & Leonard, 2007). There have been no reports of fish escape from cages in Zambia. Aquaculture development in Zambia is managed by the state Department of Fisheries under the Ministry of Agriculture and Cooperatives (Maguswi, 2003). In order to obtain a clear picture of the aquaculture development objectives in Zambia, a National Aquaculture Development Strategy (NADS) was prepared in 2004 (Halwart & Moehl, 2006). Zambia is a fish-eating nation and cage and pond aquaculture is being promoted to produce enough fish to meet the demand of the market (Maguswi, 2003). Lake Kariba offers great opportunity for aquaculture development in Zambia though there is little formal training for aquaculture development. There are five aquaculture research centres in the country that are run by the state Department of Fisheries. These are the only centres in the country where aquaculture training and research is been carried out (Halwart & Moehl, 2006). Training programmes are drawn up in close collaboration with extension officers and farmers. The research centres are supported through government grants and donor agencies. Monthly, quarterly and annual reports are submitted for follow-up actions, coupled with review of activities and verification of results (Maguswi, 2003). The Natural Resources Development College (NRDC) in Lusaka Province offers a three-year diploma course in fisheries and aquaculture while the Kasaka Fisheries Training Institute in Kafue (Lusaka Province) offers a two- year certificate course in fisheries and aquaculture for technicians expected to have regular contracts with cage fish farmers (Maguswi, 2003).

2.8.1 Tilapia Breeding Technologies in Aquaculture Development

Wild captured fisheries have reached their optimum level of exploitation and is no more seen as efficient for providing the supply of fisheries products required to meet the demand of the increasing world population (Subasinghe et al., 2009). Fish farming particularly the farming of the tilapias, has the ability to play a guided function in the struggle for adequate protein supply, reduced infant and maternal mortality rates and poverty alleviation on the Africa continent (Béné & Heck, 2005). Africa has a huge animal diversity of local fish species, but due to weak policy development for the control of these resources and genetic worn away, most fish farm species under present cultivation on the continent are genetically weak to wild, undomesticated stocks (Brummett *et al*., 2004; Lind *et al*., 2012). It is commonly agreed that fruitful fish farm establishment in Africa needs enhancement in nutritious and affordable fish feed accessibility, economics and trading conceptualization, and local professional knowledge in fish breeding and hatchery management (Lind *et al*., 2012). Another significant criterion to be taken into account is the efficient use and control of genetic materials (Ponzoni *et al*, 2011; Lind *et al*., 2012). In particular, enhanced breeds of tilapia that are fast growing, having high ability to overcome pathogens, and are good for farming in diverse fish farm environments can be best option to meet the current demand of fish protein supply (Greer & Harvey, 2004).

Tilapia, belonging to the family Cichlidae are sufficient for culture under a diverse fish farm practices because of their simplicity of breeding under natural conditions, endurance to controlling, ability to grow fast on natural as well as artificial feeds, endurance to a variety of ecosystem factors, and high acceptability, and nutrient profile (Teichert-Coddington *et al*., 1997). They are particularly sufficient for farming in third world countries because of their ability to grow fast with a short-lived generation period, endurance to a greater range of abiotic factors, low susceptibility to stress conditions and pathogens, power to give birth to offspring under culture conditions, and their ability to feed on manufactured feeds just after yolk-sac absorption (El-Sayed, 2006).

The world fish farm harvest of tilapias rose from 28,000 ton to over 3 million ton between 1970 and 2010 (Fitzsimmons, 2010). At global level, the tilapias were the largest species group harvested in freshwater inland aquaculture between 2000 and 2005, and after 2005 the harvest of cyprinids was in excess of the tilapias (FAO, 2010). On the basis of fish farm harvest, the tilapia contributed approximately 5 % of the total world fish farm production, ranking number two to the carps, which contributed over 70% (Shelton & Popma, 2006). Nevertheless, fish farm culture of tilapia on the African continent contributed roughly 19% of the global tilapia harvest from cage aquaculture (FAO, 2012).

The natural apportionment of tilapias is confined to Africa and the Middle East, with one hundred and twelve species and stocks of the genera *Oreochromis*, *Sarotherodon*, and *Tilapia* been observed (McAndrew, 2000; Pillay, 2005; Canonico *et al*., 2005; El-Sayed, 2006). Nevertheless, just a small number of the species are commercially important with still a small number of fish farm value (Shelton & Popma, 2006). The Nile tilapia (*O. niloticus),* the blue tilapia (*O. aureus),* and their diverse hybrids with *O. mossambicus* are seen as the most important fish farm species (Shelton & Popma, 2006). For instance, in China, of the designated 1.1 million ton of *O. niloticus* harvested in 2008, roughly one-fourth were a cross between Nile tilapia (*O. niloticus*) and blue tilapia (*O. aureus*) (FAO, 2010). An extremely large number of the commercially important fish farm strains have been taking widely outside their home range. Just in the 20th century, tilapias have been distributed into ninety countries for fish farming and the aquarium industry intentionally or unintentionally (Courtenay, 1997; Pullin, *et al*., 1997; De Silva *et al*., 2004). However, their inability to survive under low temperatures of less than 20 °C limits their cultivation in temperate areas (Shelton & Popma, 2006).

Two genetically enhanced tilapia varieties (GIFT and Akosombo) have been breeding with *O. niloticus* which is endemic to Africa. Specifically, the GIFT has been proven to be more economically desirable in the fish farm industry than the local tilapia varieties on the basis of how soon they attain harvestable size under culture conditions (Shelton & Popma, 2006). While these new varieties of tilapia remain possible solutions to the problems of affordable and cheap source of animal proteins and livelihood improvement on the African continent, environmentalists are worried about the possible environmental and genetic consequences on their introduction among the local tilapia strains (El-Sayed, 2006). For sustainable aquaculture development, the introduction of these new strains among the native stocks may need good knowledge on the genesis of the GIFT technology, and must account for the possible ecological and genetic consequences associated with breeding these new strains with the local stocks (El-Sayed, 2006). It is also of interest to account for the possible economic benefits of breeding these genetically enhanced varieties in Africa, looking at Ghana as an example. According to El-Sayed (2006), using a blend of the Surplus production model and Monte Carlo simulation, the net present value (NPV) of breeding the GIFT variety with local strains in Ghana accounted for roughly 1% of the country's GDP. In the past and from the socio-economic view point, the major significance of tilapia culture has been for the supply of cheap and affordable animal proteins for local consumption, with most small-scale fish farmers in over one hundred countries complementing the supply of animal proteins with tilapia (Fitzsimmons, 2006). There has also been a consistent rise among the quantity of sole proprietorship owned tilapia sales micro economies in many countries. The fish mostly are harvested from individual owned ponds or tanks, processed and taken to the market for business (Asare, 2013). The processed fish constitute a major component of dietary protein and calories in third world countries (Fitzsimmons, 2006). More usually, fresh fish will as well be on the market at the farm gate or in local markets. The tilapias have however shown significant improvements from being a cheap, nutritious food fish commonly referred to as the “aquatic chicken” (Pullin, 1985) used by non-governmental organizations to provide food for local communities in the rural areas around the globe, to an important cultivated “livestock” with yearly sales amounting to more than two billion United States Dollars in the whole world (FAO, 2010; Fitzsimmons, 2006). On the basis of livelihood significance, tilapia exceeded the salmonids in 2004, and they are noted to eventually equal the carps (Fitzsimmons, 2006). The tilapias are known to be the “main significant worldly white fish resource” (Gjoen, 2014).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Objective 1; To determine the influence of cage farming on water quality and trophic status of cage sites in Kadimo Bay, Lake Victoria, Kenya.

3.1.1 Study Area

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

The present study was conducted within Kadimo Bay (Figure 3.1), one of the bays with active cage fish aquaculture on the Kenyan side of Lake Victoria. The bay is situated between latitude 0° 6' 0'' S and longitude 34° 6'0''E and lies at an elevation of 1,133m above mean sea level (Kottek *et al*., 2006). The depth range of Kadimu bay is between 3 to 12m and about 947 km^2 in surface area, and spans a distance of 4.3km (Calamari *et al*., 1995). The shallow and sheltered nature of the bay makes it popular for cage fish farming. However, shallow and protected bays are more susceptible to eutrophication and algal bloom effects (McGlathery *et al*., 2007). The annual average precipitation around the lake basin is about 1300 mm with an average annual temperature of 22.9°C (Masongo *et al*., 2005). Most of the sheltered bays in Lake Victoria have cage fish farming as an intensive production system (Opiyo et al., 2018). The fish cages in the lake range from small (2 x 2 x 2 m) to larger ones (10.5 x 5.0 x 2.5). The main cultured species is the Nile tilapia (*O. niloticus)* (Opiyo *et al*., 2018). The fish are fed with commercial feed pellets supplemented with farmer-formulated feeds comprising of fresh water shrimp (*Caridina nilotica*). Sampling was carried out at five (Anyanga, Olele, Uwaria, Ugambe and the Utonga) cage sites within the bay that have ongoing tilapia farming, and a control site located in an area within the bay but without cage installations (Figure 3.1).

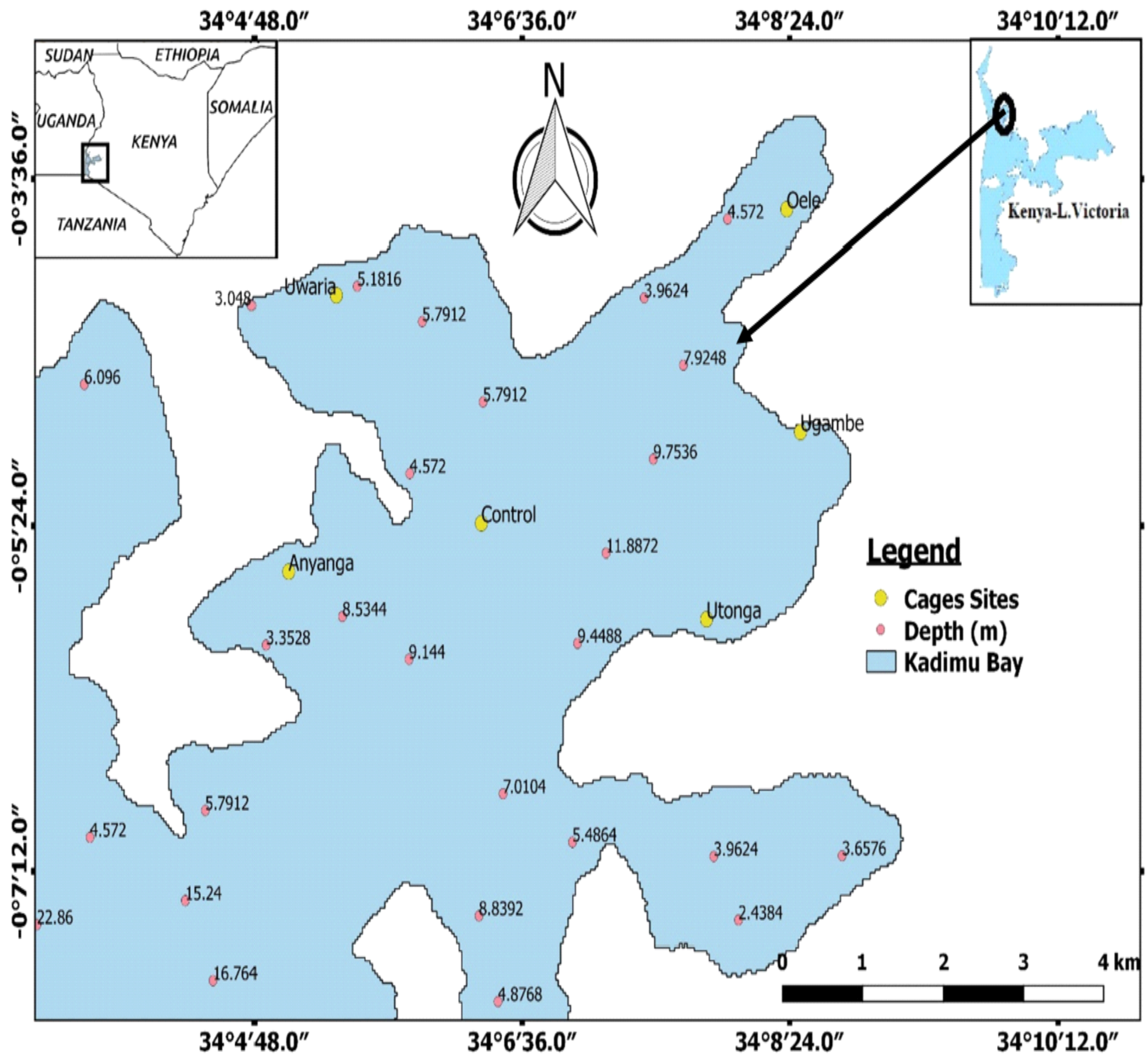

Figure 3.1: Map of Lake Victoria showing sampling sites: Anyanga, Uwaria, Oele, ugambe, Utonga and control site in the Kadimo Bay of Winam Gulf, Lake Victoria, Kenya (Modified from KMFRI).

3.1.2 Study Design

The study design was a field survey at five cage sites (Anyanga, Uwaria, Olele, Ugambe and Utonga), with a Control site. Sampling for physico-chemical variables and biological parameters was conducted at the five fish cage sites and a control site within the Kadimo Bay (Figure 3.1). The control site was far removed from the cage area, had an average depth of 9.4 m, had no fish cages, and was therefore considered as a control for the influence of cages on water quality thereby allowing for statistical inference. The cage sites had an average depth of 9.08 m and are separated by an average distance of 1.4 Km. Each cage site is managed under a different beach management unit (BMU). The sites were selected because they had on-going cage fish farming activities and were easily accessible. Sampling for water quality variables was conducted from January to October 2021. On each sampling occasion, three replicate water samples were collected with a Van Dorn water sampler at the same average depth across the sites including the control site. The samples were kept in a cooler box at approximately 4°C and transported to the Kenya Marine and Fisheries Research Institute (KMFRI) Kisumu laboratory for analysis of; chlorophyll-a, total phosphorus, nitrates, nitrites and total nitrogen concentrations. Measurements of temperature, pH, dissolved oxygen (DO), total dissolved solids (TDS), turbidity and electrical conductivity (EC) were done *in situ* with a Hanna multiparameter probe (H9829). Water transparency was measured *in situ* with a Secchi disk of approximately 20 cm diameter (Bartram and Balance, 1996). Sampling was conducted three times per site in a month for the ten months. Hence, a total of thirty water samples were analyzed per site and the control point.

3.1.3 Analytical procedures

Total suspended solids (TSS) and Particulate Organic Matter (POM) were estimated by filtering 10 mg of sample water using the GFC filters. The filters were weighed to obtain the initial weight and then sample water was filtered through them and weighed to obtain final weight, followed by oven drying and weighing to obtain the ashed weight. TSS was estimated as the difference between final weight and initial weight, while POM was estimated as the difference between final weight and ashed weight following the methods in APHA (2005) and Rodier *et al*. (2009).

The molybdenum blue procedure was used to estimate the soluble reactive phosphorus (SRP), while the dichloroisocyanurate-salicylate procedure was used to estimate the ammonium ion concentrations in the samples (APHA, 2005). The cadmium reduction procedure and the azo-dye complex techniques were used to estimate nitrates and nitrite concentrations by running sample water through a cadmium column filled with coated metallic copper (APHA, 2005). UV Spectrophotometer (Genesys 10S Vis SN-2F1N308001) was used for the analysis of chlorophyll-a, total phosphorus (TP), and total nitrogen (TN). Alkaline potassium persulphate was used to digest TP through a high temperature process thereby converting all phosphorus compounds to orthophosphate and allowing it to react with molybdic acid and ascorbic acid which is reduced to phosphomolybdae, and the absorption read at 885nm (APHA, 2005). The same procedure was followed for the analysis of TN. Partitioning of chlorophyll-a was done by the sonication technique and the effective concentration determined by the Lorenzen equation (APHA, 2005) through the application of absorbance readings from the UV Spectrophotometer (Rodier *et al*., 2009).

3.1.4 Nutrient limitation and trophic state evaluation

Nutrient availability and limitation in the bay were evaluated using the TN: TP ratio (OECD, 1982; Reynolds, 1999). TN limitation was considered probable when molar TN: TP < 10 and TP limitation when TN: TP > 20 (Maberly *et al*., 2020). *The* intermediate ratios indicate potential co-limitation between TN and TP (Maberly *et al*., 2020). The Carlson's Trophic State Index (CTSI), a measure of trophic state of a site was estimated using data on the TP, chlorophyll-a (as a measure of primary production), and Secchi disk (SD) readings (Carlson, 1977). The required limits for designation of a trophic state were adapted from the recommendations in Carlson and Simpson (1976). The trophic state index (TSI) values describe the water quality state of sites by estimating the productivity of the water based on algal biomass. The algal biomass was calculated using empirical equations and using the concentration of chlorophyll-a, Secchi disk depth or water transparency, and total phosphorus values of sites (Carlson, 1977). The trophic state (TS) groupings based on the CTSI values are shown in Table 3.1.

Table 3.1: Carlson's trophic state classification scheme (Carlson, 1977) used to classify the trophic states of cage sites in Kadimo Bay, Lake Victoria. Kenya

Carlson's trophic state index	Lake trophic state index	Attributes
<30	ultra-oligotrophic	Clear water, oxygen in hypolimnion throughout the annual cycle.
30-40	Oligotrophic	Oligotrophy, but some shallow lakes may become anoxic during dry season.
40-50	Mesotrophic	Water moderately clear, but increasing occurrence of anoxia during dry season.
50-60	Light eutrophic	Decrease transparency, warm water fisheries only.
60-70	Medium eutrophic	Possibility of algae blooms during dry season tending towards hypereutrophic state.
70-80	Heavy eutrophic	Decreasing macrophyte species, occurrence of alga scum, and loss of cultured fish.
>80	Hypereutrophic	Increasing alga blooms, eutrophication of the water is evident.

The TSI was first calculated separately based on each of the three parameters (Chlorophyll-a, $\mu g L^{-1}$; TP, $\mu g L^{-1}$; and Secchi disk depth, SD, m) and the overall CTSI for each site evaluated from the average of the three separate values as shown below (Carlson, 1977):

$$\text{TSI (SD)} = 10\left(6 - \frac{\ln SD}{ln2}\right) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2)$$

$$\text{TSI }(Chl - a) = 10\left(6 - \frac{2.04 - 0.68 \ln \text{Chl} - \text{a}}{ln2}\right) \ldots \ldots \ldots \ldots \ldots \ldots (3)$$

$$\text{TSI }(TP) = 10\left(6 - \frac{\ln\frac{48}{TP}}{ln2}\right) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4)$$

$$Site\ CTSI = \frac{TSI\ (SD) + TSI(Chloro - a + TSI(TP)}{3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

3.1.5 Data treatment and statistical analysis

Water quality variables in the bay were evaluated using the national (Aura, 2020) and international (WHO, 2008, 2011) recommended limits for ecosystem functioning and services. Two-way analysis of variance was performed on log (x + 1) transformed data to test for significant differences in physico-chemical variables and CTSI among the sites and months of sampling, with sites and months as main factors and interaction between sites and months. The means of the factor with significant effect ($p < 0.05$) were then compared either between sites or months using one-way ANOVA, and Turkey-Kramer multiple comparison *post hoc* test used to tease out the significant variables within sites or months. Where monthly effects were significant (See Table S1), the temporal pattern of variations of the variables were examined using a graphical plot. Log-transformation and Levene's test were used to achieve normality and to test homoscedasticity assumptions of ANOVA (Zar, 1999). All graphical plots were implemented in the Sigma Plot software.

3.2 Objective 2 and 3: To estimate the phosphorous assimilation load and fish production carrying capacity of fish cage sites in Lake Victoria, Kenya

3.2.1 Sampling procedures and Analytical methods

The data used for the estimation of phosphorus assimilation load and fish production carrying capacity was partly obtained from the sampling procedures and analytical methods for total phosphorus already described in sections 3.1.2 and 3.1.3.

3.2.2 Calculation of Phosphorus-based carrying capacity

Phosphorus is a critical element needed by fish for optimum growth and development (Pillay, 2005). It is often a limiting nutrient in freshwater bodies that controls phytoplankton production and together with light, optimizes the productivity of aquatic ecosystems (Beveridge, 2004). Over supply of phosphorus leads to non-linear feedbacks that results into negative responses like eutrophication and water quality deterioration (Volleinweider, 1998; Beveridge, 2004; Pillay, 2005). Phosphorus-based carrying capacity (mg m^3) is the TP assimilation potential of an area that will not disrupt the ecological functioning of the area (Beveridge, 2004). Total phosphorus load of a site is simply quantified by multiplying the site area by unit concentration of TP in the water. The TP assimilation load of the five cage sites within the study area were therefore estimated following the mass-balance equation modified from Dillon and Rigler (1975) and as applied by Beveridge (2004) and Pulatsu (2003) as:

$$\text{Lfish} = \frac{\Delta[P]Z\emptyset}{1-Rfish} \quad (6)$$

Where:

Lfish = Cage site carrying capacity (maximum assimilation load) of total phosphorus (mg m^3 $year^{-1}$).

Δ [P] (mg m^{-3}) = Total phosphorus allocation load, obtained from the difference between measured phosphorus $[P]_c$ and the maximum allowable phosphorus load $[P]_i$ for fish culture as:

$$\Delta[P] = [P]i - [P]c \quad (7)$$

Z (m) = Average depth of a cage site

$\emptyset$ ($year^{-1}$) =Flushing coefficient, a measure of the water replacement rate at a site. Estimated from average water debit (Q, m^3 $year^{-1}$) and water volume at sites (V, m^3) as:

$$\emptyset = Q/V \quad (8)$$

R_{fish} = Proportion of total phosphorus left in sediments as a result of feeding fish in the cages and from fish waste matter estimated according to Beveridge (2004) and Pulatsu (2003) as:

$$Rfish = X + [(1 - X)]R \quad (9)$$

Where,

X: the net proportion of total phosphorus lost permanently to the sediments as a result of solid deposition and is estimated to be ranging between 0.4-0.5 (Pulatsu, 2003).

R: Phosphorus retention coefficient given by:

$$R = \frac{1}{1+0.747Ø\,\hat{}\,0.507} \quad \text{(10)}$$

The effective quantity of total phosphorus discharged in the environment from fish aquaculture waste (Pe) is directly proportional to fish production and is given by the equation (Beveridge, 2004):

$$Pe = (Pfeed\ x\ FCR) - Pfish \quad \text{(11)}$$

Where:

Pe = TP released into the environment from a ton of fish produced (kg of TP per ton of fish production).

FCR = Feed conversion ratio generated from the ratio of feed given and the amount of fish produced.

P_{feed} = TP in fish feeds (kg ton^{-1})

P_{fish} = TP incorporated into the body of whole fish (kg ton^{-1})

3.2.3 Data sources for calculation of Phosphorus-based carrying capacity

The variables for the estimation of phosphorus-based carrying capacity per site using the mass-balanced model (equation 1) were derived through fieldwork activities and from the published and grey literature. The surface area and water volume at each cage site were estimated in cooperation with KMFRI using the planimetry method. The average depth (Z, m) of cage sites were estimated during sampling using a depth finder.

The average water debit (Q, m^3 $year^{-1}$) for the cage sites used to derived the flushing rate (Ø) in equation 3 was determined from the average of published data on the lake's water balance parameters for comparable sites to Kadimo Bay and included; long-term average inflow from catchment surface runoff (Ad.r), cage site surface area (A), Precipitation into the lake (Pr), and Evaporation from the lake (Ev) (Table 3.2). The variables were incorporated in the equation below as (Dillon and Rigler, 1975; Shoji, 2009).

$$Q = Ad.r + A\ (Pr - Ev) \quad (12)$$

Table 3.2: Published estimates of the mean annual water balance parameters of Lake Victoria, and their reference sources. Adopted from Xungang and Nicholson (1998)

Period	Rainfall Over lake (mm/year)	Evaporation (mm/year)	Tributary inflow (mm/year)	Reference source
	1420	1350	230	Hurst (1952)
	1145	1130	237.5	
1925-1959	1630	1523	260	de Baulny and Baker (1970)
	1650	1500	250	Hastenrath and Kutzbach (1983)
	1636	1459.5	238	WMO (1974, 1981)
	1450	1370	260	Spigel and Coulter (1996)
1956-1978	1810	1593	343	Howell *et al.* (1988)
1945-1984	1645	1470	0	Flohn and Burkhardt (1985)
1950-1979	1660	1590	420	Kite (1982)
1970-1974	1850	1595	343	Piper *et al.* (1986)
1956-1978	1476	1401	241	Balek (1977)
Mean	1579.27	1452.86	256.59	

Analysis of TP in feed (Pfeed) and TP in the body of whole fish (Pfish) (equation 6) was done at the KMFRI laboratory. Consequently, the TP in feed used by cage fish farmers was estimated to be about 21.75 kg ton^{-1}, while TP in the body of whole tilapia was estimated at about 3.5 kg ton^{-1}.

3.2.4 Calculation of Cage site Phosphorus Assimilation Load

The mass-balanced model in Equation (6) was applied to derive the total phosphorus (TP) assimilation capacity for the five sites within Kadimu Bay. An example of how TP assimilation capacity was derived for each of the five cage sites in the bay is shown for Anyanga site (Figure 3.1) for location as follows:

For Anyanga, the TP assimilation Lfish, in Equation (6) was derived from the following steps:

The TP allocation load Δ [P] was derive as 13.44 mg m^{-3} from the difference between maximum allowable TP allocation load of 100 mg m^{-3} recommended for Lake Victoria Kenya cage aquaculture by the Kenyan Marine and Fisheries Research Institute (Aura, 2020), and the highest measured field value of 86.56 mg m^{-3} at the site. The highest field values of TP at sites were used in order to provide precautionary estimates of TP assimilation carrying capacities.

Given the average depth (Z) of 7.01 m for Anyanga site and flushing rate (Ø), Equation (8) of 18.03 $year^{-1}$ derive from water debit (Q) of 78 059 569.28 m^3 $year^{-1}$ from equation (12) and water volume (V) of 4 328 738.09 m^3 (Tables 3.3), the phosphorus retention coefficient (R) was derived as 0.24 from equation (10). Consequently, R_{fish} (Equation 9), the proportion of TP left in sediment was derive as 0.62 taking X in equation 9 as 0.5. Therefore, the amount of TP that can be carried by the lake at Anyanga site (Lfish) was estimated by substituting the above variables into equation (6) as 4.47 g m^{-2} $year^{-1}$ (Table 3.4). This value was multiplied by the cage site surface area of 617 509 m^2 to derive the site overall TP assimilation load.

Table 3.3: Parameters for calculation of total phosphorus assimilation carrying capacity for cage sites in the Kadimo Bay, Lake Victoria, Kenya

Site	Surface area (m^2)	Depth (m)	Volume (V) (m^3)	Water Debit (Q) (m^3/year)	Flushing rate(Ø =Q/V) ($year^{-1}$)
Anyanga	617509	7.01	4328738.09	78059569.28	18.03
Oele	22458	4.27	95895.66	2839172.37	29.61
Ugambe	9250	8.84	81770	1169549.09	14.30
Utonga	29122	10.67	310731.74	3681568.61	11.85
Uwaria	137022	4.7	644003.4	173321207.61	26.89

Table 3.4: Total Phosphorus (TP) assimilation carrying capacity and hydrological parameters of cage sites within Kadimu Bay, Lake Victoria, Kenya

Site	TPmax (mg/m^3)	ΔP(mg m-^{3})	Z(m)	Ø(year^1)	R	R_{Fish}	Lfish (g/m^2/year)
Anyanga	86.56	13.44	7.01	18.03	0.24	0.62	4.47
Oele	96.61	3.39	4.27	29.61	0.19	0.595	1.058
Ugambe	97.38	2.62	8.84	14.3	0.26	0.63	0.895
Utonga	82.93	17.07	10.67	11.85	0.28	0.64	5.995
Uwaria	55.16	44.84	4.7	26.87	0.2	0.6	14.167
Kadimo Bay	83.73	16.27	7.098	20.132	0.234	0.617	6.07

All notations are as explained in the text.

Following Equation (11) for the amount of TP generated per ton of fish produced, and given the TP in feed (P_{feed}) as 21.75 kg ton^{-1}, FCR value of 1.4 and TP in the body of whole fish (P_{fish}) as 3.5 kg ton^{-1}, the TP released in the environment per ton of fish produced (Pe) at the site was estimated at 26.95 kg ton^{-1}. Consequently, the total phosphorus assimilation capacity for Anyanga site based on fish production is derived from the ratio of TP assimilation load for the site and the quantity of phosphorus released per ton of fish produced.

From consultations and the literature e.g (Orina *et al*., 2018), the annual cage fish production at Anyanga site (Pe x fish production) releases TP to the environment at the site. The amount of TP release to the environment as a result of cage fish production was compared to the TP assimilation capacity derived from the mass-balance model to decide on whether the TP assimilation capacity is been exceeded or below the TP release to the environment as a result of cage fish production. The TP assimilation capacity for each of the other four sites, the TP released by current fish production at sites, were calculated in the same computational procedure.

3.3 Objective 4: To evaluate the effect of stocking density on the growth performance and survival of Nile tilapia (*O.niloticus)* in experimental cage Lake Victoria, Kenya

3.3.1 Description of experimental set up at the Study Site

The study was specifically done at the Anyanga fish cage site located in the Kadimo Bay (Figure 3.2), showing the map of Kadimo bay, Lake Victoria Kenya with cage sites and the experimental layout of the experimental cages at the Anyanga experimental site.

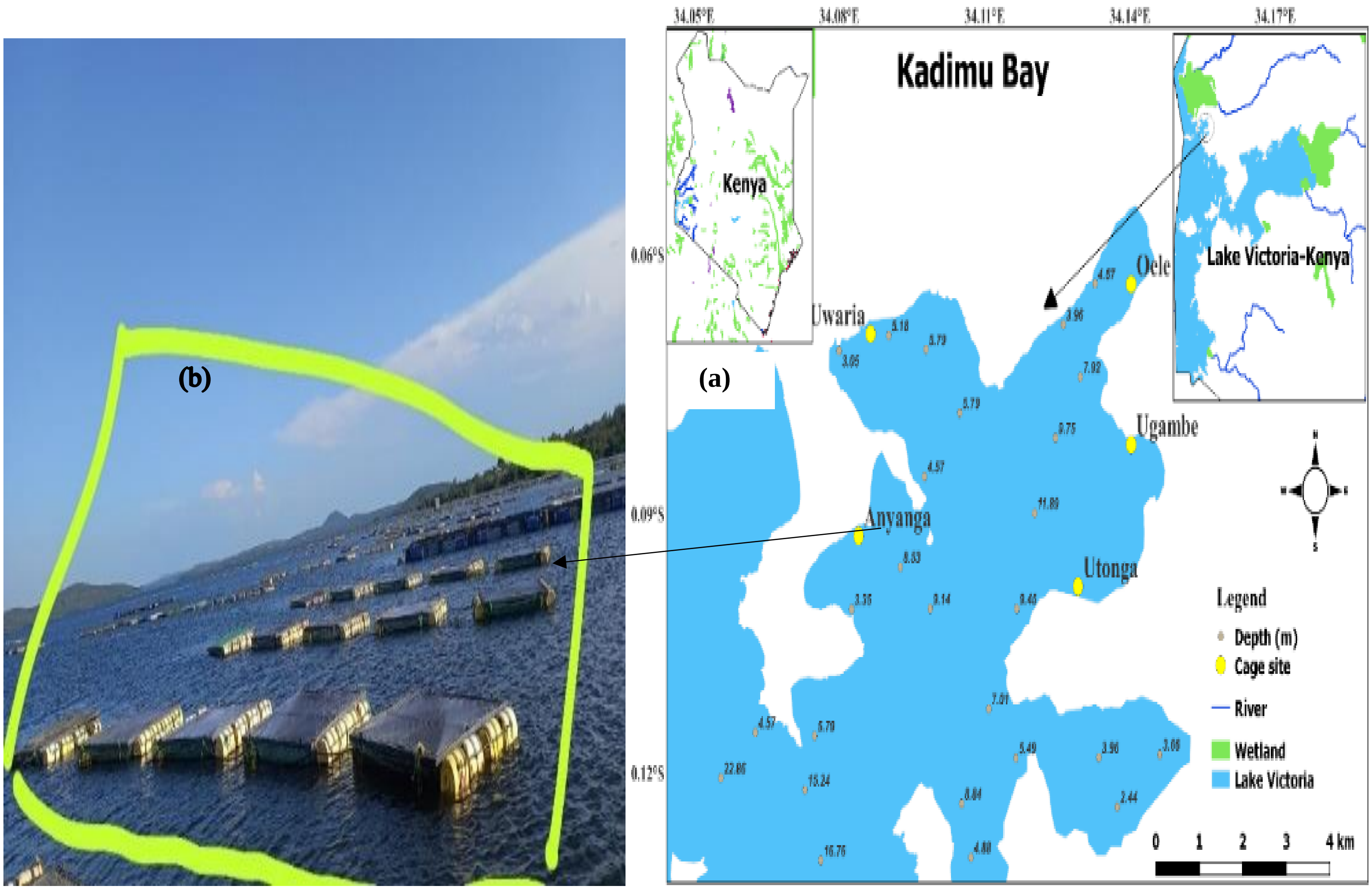

Figure 3.2: (a) Map of Kadimo Bay, Lake Victoria Kenya, showing the cage fish sites, and (b) the layout of experimental cages at the Anyanga experimental site

3.3.2 Experimental Design for growth studies

The experiment on fish growth was done at Anyanga site (Figure 3.2). This is one of the cage sites already described on section 3.1.1. Anyanga site was chosen because of relative ease of accessibility and the cooperation of the Beach Management Unit (BMU) personnel at the site. The site already has about 450 privately 0wned fish cages. The experiment was done in fifteen (15) floating net cages each measuring 2m x 2m x 3m and which were laid in lines parallel to the shore (Figure 3.2b), fabricated with metal frames and synthetic nylon net (mesh size 1.2m) were installed in the Lake. Each cage was suspended to sinkers and plastic drums were used to keep the cages buoyant with stocking densities of 50, 75, 100, 125 and 150 fish per m^3 hereinafter referred to as; D50, D75, D125, D150 and D100 (control). The D100 treatment represented the common stocking density used by the farmers in the lake and was therefore considered a control treatment. Treatments were replicated three times and the random number table was use to achieve randomization. *O. niloticus* fingerlings were procured from the local JEWLET FISHERIES ENTERPRISE LTD and acclimatized in cages installed in the lake for two months (December, 2021 to January, 2022) before experimentation.

After acclimatization, the fingerlings of mean (±SD) initial weight of 5.5 ± 1.72 g and mean initial length of 6.8 ± 0.63 cm were transferred in the experimental cages using the completely randomized design approach (Zar, 1999) in order to minimize experimenter induced biases. The fingerlings were consequently reared for a period of eight months (February to September, 2022). During rearing, a commercial feed (Skretting Nutra) with crude protein level of 44% and lipid of 6.27% was used to feed the fish. The fish were fed to satiation thrice a day at 9:30am, 12:30pm and 3:30pm until they attained a mean weight of 5.6 ± 1.76 g. Thereafter, a feed ratio of 5% of fish body weight was applied (Riche *et al.*, 2004). Fish from the cages were sub-sampled fortnightly for weight and length measurements by taking about 15% of the fish using a scoop net. Weight was measured with an electronic scale (6kg, 0.1g CGOLDENWALL high precision Digital Accurate Analytical) to the nearest 0.1 g and length with a measuring board to the nearest 0.01cm after gently blotting each fish with a wet towel. The fish were placed back to their respective cages after measurements. At the end of the culture period, all the fish in each cage were weighed individually and the total number of fish surviving counted. During each fortnightly sampling, numbers of dead fish were noted, if any, and recorded.

3.3.3 Measurement of water quality variables at experimental cage site

Physico-chemical water quality parameters were recorded *in situ* in the cage fortnightly in the morning and evening to determine the influence of environmental variability on growth. Temperature, pH, dissolved oxygen (DO), total dissolved solids (TDS), turbidity and electrical conductivity (EC), were measured with a Hanna multiparameter probe (H9829). Water samples were collected bi-weekly for analysis of nutrients (nitrite, nitrate and ammonia). The samples were placed in a cooler box and transported to the laboratory for analysis of nitrite, nitrate and ammonia contents. The cadmium reduction procedure and the azo-dye complex technique (APHA, 2005) were used to estimate nitrate and nitrite concentrations, respectively, while the dichloroisocyanurate-salicylate procedure was used to estimate the ammonia concentration in the water samples (APHA, 2005).

3.3.4 Data treatment

The growth and survival rates of the fish in the cages were derived using the relationships below:

(a) Weight gain (g) = final fish weight -initial fish weight

(b) Average daily weight gain (g) = (final fish weight-initial fish weight)/culture period in days.

(c) Specific Growth Rate (% per day) = 100 × (ln W2-ln W1)/T2-T1

Where: W1= Initial live body weight (g) at time T1 (days)

W2= Final live body weight (g) at time T2 (days)

(e) Fish survival (%)= $\frac{\text{Number of survivors at the end of culture period}}{\text{Number of fish stocked}}$ x 100

(f) $\text{Feed conversion Ratio} = \frac{\text{weight of feed fed (kg)}}{\text{weight gain of fish (kg)}}$

(g) Fish production (kg) = Final mean weight * Number of fish in the cage.

(h) Condition factor (K) = 100* aL^b

Where; a is the intercept of the Length-weight relationship and b the slope.

3.3.5 Economic Analysis of fish production

At the end of the experiment, an economic analysis was done to estimate the Cost-benefit ratio for different stocking densities on the basis of the Cost of fish production per kilogram (kg) of fish, computed from the product of the FCR and the cost of feed per kg, and the cost of fish per kg from the sale of fish for one production cycle.

The Cost-benefit ratio was estimated as:

Benefit-cost ratio (BCR) = Cost of fish production per kg / Cost of fish sale per kg.

3.3.6 Statistical Analysis

The mean weights of the fish in each treatment were compared for significant differences at the end of the experiment using one-way analysis of variance (ANOVA) for objective four after log-transformation (log x+1) of data to approximate normality of the distribution. The means of treatments with significant effect ($p < 0.05$) were then determined using the Tukey-Kramer multiple comparison *post hoc* test.

CHAPTER FOUR

RESULTS

4.1 Influence of cage farming on water quality and trophic status of cage sites (Anyanga, Olele, Uwaria, Ugambe and Utoga) in Kadimo Bay, Lake Victoria, Kenya.

4.1.1 Water quality variables and standard limits

The results showed most of the physico-chemical variables had no significant difference between months or sites (Table S1). Seventeen (17) variables (pH, DO, TDS, Turbidity, Conductivity, POM, Temp., TSS, SRP, TN, TP, NO_2^-, NO_3^-, NH_3, NH_4^+, SiO_4^{4-} and Chlorophyll-a) were not significantly different ($p > 0.05$) among months of sampling, while fourteen (14) variables (Temp., pH, DO, Turbidity, POM, NH_4^+, SiO_4^{4-} TSS, SRP, TN, TP, TSS, $NO_3^-$and NH_3) were also not significantly different ($p > 0.05$) among sampling sites (Table S1). Only three variables (chlorophyll-a, conductivity and nitrites) exhibited significant difference between sites but not months (Table 4.1, Table S1). There were no significant interactions between sites and months for all the variables (Table S1). Electrical conductivity was significantly lower ($p < 0.05$) at the control site than the fish cage sites. The mean values of eleven parameters (pH, Temperature, TDS, TSS, Chlorophyll-a, EC, Turbidity, Nitrates, Nitrites, Total nitrogen, and Ammonium), were all within the recommended threshold for aquatic life at all sites (Table 4.1) indicating lack of negative influence of the cages on these environmental conditions in the bay. Total phosphorus (TP) concentrations were above the standard limit for aquatic life of 50 µg L^{-1}, while dissolved oxygen (DO) concentration showed no significant difference ($p > 0.05$) between sites but were above the minimum threshold limit (6.0 mg L^{-1}) recommended for aquatic life (Table 4.1).

Table 4.1: Statistical summary of physico-chemical parameters of aquaculture sites in the Kadimo Bay, Lake Victoria, Kenya sampled from January, 2021 to October, 2021. Bold figures represent variables that are significantly different ($p < 0.05$) between sites. Values represent mean ± SD. Means with different letters across table are significantly different.

SITE	Anyanga	Oele	Uwaria	Ugambe	Utonga	Control	ANOVA		
							F	P	Threshold Standard for aquatic life
DO(µg/L)	7.06± 0.61	7.25± 0.56	7.58± 0.45	7.29± 0.93	6.78± 1.32	7.67±0.46	0.37	0.861	6[1.23.4]
Temp (0^{C})	26.61±0.87	26.65±0.81	26.63±0.80	26.60±0.65	26.72±0.88	26.70±0.95	0.18	0.965	
Acidity (H^{+})	7.63±0.19	7.63±0.24	7.72±0.28	7.78±0.57	7.88±0.52	7.71±0.24	0.94	0.482	6.5-9.0[1,2,3]
TDS (µg/L)	65.9±4.16	66.9±3.33	65.8±5.05	66.2±4.12	63.9±5.20	66.89±3.74	1.33	0.303	500[1]
Turb. (FMU)	3.56±1.44	3.43±1.44	3.86±1.67	3.80±1.13	3.33±1.08	1.95±0.83	0.26	0.930	5[1]
EC (µs/cm)	**110.31±1.62**^{A}	**112.84±1.94**^{A}	**110.09±2.27**^{A}	**107.47±5.70**^{A}	**105.42±5.32**^{A}	**97.53±4.17**^{B}	9.91	0.000	1500[3]
TSS (µg/L)	4.87±0.37	4.91±0.64	4.25±0.76	4.71±1.12	4.25±0.46	3.43±0.97	1.46	0.259	<30[1,2,3,4]
POM(µg/L)	1.99±0.16	1.84±0.24	1.57±0.15	1.88±0.24	1.64±0.14	1.65±0.33	1.17	0.369	
Chl-a (µg/L)	**1.71±0.16**^{B}	**2.13±0.84**^{B}	**11.26±4.80**^{A}	**2.99±2.56**^{B}	**2.69±1.31**^{B}	**2.22±0.63**^{B}	4.78	0.008	<12[1,2]
SRP (µg/L)	15.6±4.0	17.07±6.55	19.7±8.47	17.1±7.59	12.6±3.82	10.84±1.42	1.01	0.448	
NO_3^- (µg/L)	7.35±2.82	10.09±1.67	7.54±1.43	7.72±3.84	7.80±2.79	7.53±1.09	2.63	0.067	<1000[1,4]
NO_2^- (µg/L)	**5.45±1.30**^{AB}	**5.34±1.16**^{AB}	**6.35±0.96**^{A}	**5.62±0.63**^{AB}	**3.16±2.25**^{AB}	**2.68±1.39**^{B}	4.18	0.014	<100[1,4]
TN (µg/L)	332.54±26.0	344.36±29.6	277.55±49.3	349.71±37.43	335.51±21.7	254.67±31.93	1.88	0.158	4000[5,6]
TP (µg/L)	86.79±2.20	108.77±46.6	121.08±50.59	96.29±23.5	84.19±8.65	78.22±8.55	1.30	0.315	50[4,5,6]
NH_3(µg/L)	21.89±6.77	20.46±8.32	22.84±10.63	18.80±3.28	18.70±4.73	19.13±5.46	0.03	0.999	<10-1150[7]
NH_4^+(µg/L)	17.44±3.75	24.14±8.38	18.60±3.90	19.48±4.13	18.22±2.65	16.93±2.13	0.75	0.596	<1000[1,4]
SiO_4^{4-} (mg/L)	13.26±1.04	15.14±1.60	14.75±2.04	15.55±1.34	13.96±2.81	13.44±1.88	2.37	0.054	

For the three variables that showed significant differences between sites, nitrite had a minimum value at the control site (2.68 ± 1.39 µg L^{-1}) and a maximum of 6.35 ± 0.96 µg L^{-1} at Uwaria with an overall mean of 4.77 ± 1.35 µg L^{-1} among the six sites. Electrical conductivity (an indirect measure of pollution) varied from a minimum of 97.53 ± 4.17 µS cm^{-1} at the control site to a peak of 112.84 ± 1.94 µS cm^{-1} at Olele site with an overall mean of 107.27 ± 4.94 µS cm^{-1} among sites. Chlorophyll-a (a measure of system productivity) had minimum value at the control site (2.22 ± 0.63 µg L^{-1}) and peaked at the Uwaria cage site (11.26 ± 4.80 µg L^{-1}, Table 4.1) with an overall mean of 3.83 ± 3.34 µg L^{-1} among the sites. Turkey-Kramer *post hoc* test indicated conductivity differed significantly ($p < 0.05$) only at the control site, while chlorophyll-a and nitrates differed at Uwaria and the control site (Table 4.1).

4.1.2 Trophic state of cage sites

The five cage sites in the bay exhibited mean (±SD) CTSI of 55.23 ± 2.04, ranging from 53.83 ± 14.02 at the Utonga site to 59.27 ± 12.36 at the Uwaria site (Table 4.2), suggesting a light eutrophic status of the sites, based on the thresholds shown in Table 3.1. The control site, exhibited a mean CTSI value of 53.14 ± 12.08, also indicating a light eutrophic state similar to the cage sites. The CTSI values indicated the Uwaria cage site (see Figure 3.1 for site locations) had the highest index value, while the Utonga site had the lowest. A Turkey–Kramer *post hoc* test indicated the Uwaria site exhibited a significantly different CTSI value, but was still indicative of a light eutrophic state (Table 4.2). Based on individual variable (chlorophyll-a, TP, secchi depth) contributions to the overall CTSI, TP contributed most to the CTSI values, with a mean trophic state based on TP ranging between 68.12 ± 2.07 and 73.39 ± 8.43 among the sampling sites (Table 4.2).

Secchi depth, a measure of water transparency, provided the second highest contribution to the CTSI of the sites, exhibiting TSI values ranging between 52.78 ± .83 and 54.17 ± 8.4 among the sampling sites (Table 4.2).

Table 4.2. Carlson's Trophic State Index (CTSI) values and Trophic State Index (TSI) values of variables at cage sites in the Kadimo Bay, Lake Victoria, Kenya. Means across table with different letters are significantly different

	Cage samlping sites						Tukey–Kramer	
Parameters	Anyanga	Uwaria	Oele	Ugambe	Utonga	Control	*F*	*p*
TSI (Chla)	40.54±5.51[b]	50.40±7.34[a]	40.68±4.96[b]	40.19±3.84[b]	40.09±3.52[b]	38.00±3.82[b]	16.99	0.000
TSI (SD)	53.45±1.21	54.02±1.44	54.17±0.84	52.78±0.83	53.28±1.52	53.84±1.36	0.95	0.454
TSI (TP)	68.47±0.44[b]	73.39±8.43[a]	69.43±1.60[b]	69.43±1.78[b]	68.12±2.07[b]	67.57±1.11[b]	5.98	0.000
CTSI	54.15±13.98[b]	59.27±12.36[a]	54.76±14.38[b]	54.13±14.67[b]	53.83±14.02[b]	53.14±12.08[b]	9.93	0.000
TROPHIC STATUS	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic		

The eutrophic status for all the months showed a light eutrophic state around the cage sites, although some months showed a significantly different intensity of the eutrophic status from the others (Table 4.3). The overall monthly CTSI exhibited a mean (±SD) of 54.67 ± 1.54, varying from 52.63 ± 13.53 in July to a peak of 57.49 ± 10.85 in March. The bay CTSI was significantly lower in February, April and July, based on the Turkey–Kramer *post hoc* test. The contribution of the Secchi depth transparency to the CTSI was not significantly different between the sampling months (Table 4.3), although the chlorophyll-a and TP contributions varied between the months. The chlorophyll-a contribution to the monthly trophic states of the bay (TSI Chl-a) was significantly different and lower during April–July, while the TP contribution (TSI TP) was only significantly different and higher in January and March (Table 4.3).

Table 4.3: Carlson's Trophic State Index (CTSI) values and Trophic State Index (TSI) values of variables for sampling months in the Kadimo Bay, Lake Victoria, Kenya. Means across table with different letters are significantly different.

	Sampling months										Turkey-Kramer	
Parameters	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	F	P
TSI (Chl-a)	42.11±11.74^{a}	42.92±1.41^{a}	46.46±7.84^{a}	36.98±1.12^{b}	39.12±2.12^{b}	41.22±10.05^{b}	35.72±3.55^{b}	46.34±2.49^{a}	42.42±2.39^{a}	42.47±0.56^{a}	18.84	0.000
TSI (SD)	54.18±0.79	52.97±1.08	53.78±1.05	52.97±1.08	53.04±0.07	53.11±2.29	53.30±1.47	53.24±0.73	53.88±1.16	54.19±0.78	0.96	0.343
TSI (TP)	73.73±6.76^{a}	67.87±2.39^{b}	72.25±6.87^{a}	68.58±1.13^{b}	68.76±0.18^{b}	68.94±1.36^{b}	68.86±1.42^{b}	68.25±0.72^{b}	67.64±1.24^{b}	68.67±0.16^{b}	0.83	0.000
CTSI	56.67±13.02^{a}	54.59±10.25^{b}	57.49±10.85^{a}	52.84±12.90^{c}	53.64±12.11^{b}	53.42±11.35^{b}	52.63±13.53^{c}	55.94±9.15^{b}	54.65±10.31^{b}	54.78±11.11^{b}	8.44	0.000
Trophic status	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic	Light eutrophic		

4.1.3 Pearson's linear correlation matrix

The Pearson's linear correlation matrix suggest a strong positive linear relationship between total phosphorus concentration and chlorophyll-a and soluble reactive phosphorus (Table 4.4). However, there was a strong negative correlation between turbidity and temperature as well as between oxygen reduction potential and pH at $p < 0.01$. Turbidity was negatively correlated pH ($p < 0.001$). There was a weak correlation between the remaining variables with no significant effects.

Table 4.4: Pearson's linear correlation matrix of physicochemical water quality variables derived for the Kadimo Bay Lake Victoria, Kenya from October, 2020 to June, 2021.

	Temp(^{0}C)	PH	DO (mg/L	TDS (ppm)	Turbidity (fmu)	Cond.µS/cm	Salinity (psu)	ORP (mv)	Secchi disc (m)	TSS (mg/L)	POM (mg/L)	Chlorophyll a (µgL^{-1})	SRP(µgL^{-1})	NO_3- (µgL^{-1})	NO_2- (µgL^{-1})	NH_3 (µgL^{-1})
Temp(^{0}C)	1.00															
PH	0.56	1.00														
DO (mg/l	0.15	-0.50	1.00													
TDS (ppm)	0.21	-0.11	0.39	1.00												
Turbidity (fmu)	-0.84**	-0.59***	0.05	-0.03	1.00											
Conductivity (microsimen/cm	-0.01	-0.30	0.34	0.59	0.19	1.00										
Salinity (psu)	0.06	0.12	0.01	0.06	-0.06	0.05	1.00									
ORP (mv)	-0.44	-0.84**	0.26	0.07	0.44	0.30	-0.35	1.00								
Secchi disc (m)	0.00	0.04	-0.11	-0.05	0.05	0.00	0.13	-0.23	1.00							
TSS (mg/L)	-0.48	-0.20	-0.14	0.17	0.56	0.37	0.13	0.19	0.03	1.00						
POM (mg/L)	0.12	0.02	0.24	-0.01	-0.05	-0.05	0.10	-0.21	-0.01	0.10	1.00					
Chlorophyll a (µgL^{-1})	0.05	-0.13	0.18	0.05	-0.07	0.14	-0.13	0.24	-0.19	0.00	0.01	1.00				
SRP(µgL^{-1})	0.45	0.45	-0.14	0.06	-0.54	0.06	0.22	-0.36	0.09	-0.13	0.07	0.61	1.00			
NO_3- (µgL^{-1})	-0.34	-0.24	0.00	0.38	0.47	0.47	-0.23	0.32	-0.19	0.44	-0.11	0.40	0.04	1.00		
NO_2- (µgL^{-1})	-0.37	-0.46	0.13	0.27	0.55	0.53	-0.27	0.56	-0.07	0.45	-0.11	0.35	-0.10	0.84	1.00	
NH_3 (µgL^{-1})	0.66	0.33	0.21	0.25	-0.63	0.06	0.10	-0.32	0.01	-0.19	0.34	0.09	0.44	-0.40	-0.33	1.00
Ammonium(µgL^{-1})	0.36	-0.01	0.07	0.07	-0.37	0.14	-0.25	0.16	-0.04	-0.24	0.15	0.58	0.65	0.11	0.14	0.32
TN(µgL^{-1})	0.32	0.46	-0.17	-0.09	-0.36	-0.16	0.04	-0.56	0.03	-0.24	0.03	-0.69	-0.23	-0.47	-0.55	0.24
TP(µgL^{-1})	0.39	0.04	0.21	0.19	-0.39	0.18	-0.03	0.11	-0.02	-0.15	0.09	0.75	0.73	0.22	0.24	0.34
Silicate(mgL^{-1})	0.17	0.02	0.22	0.20	-0.18	0.30	-0.17	-0.04	0.24	0.03	0.04	0.25	0.34	-0.04	0.13	0.38

***p<.001; **P<.01; *p<.05

4.1.4 Relationship between chlorophyll-a, total phosphorus (TP) and nitrates

The relationship between chlorophyll-a (Chl-a), TP and nitrate (NO_3) concentrations for all sites combined is illustrated in Figure 4.1. There was a moderate relationship between the concentration of chlorophyll-a and TP at all sites combined (R^2 = 0.50), possibly indicating a less strong limitation of TP on chlorophyll-a abundance in the bay (Figure 4.1). The nitrate concentrations exhibited a relatively stronger relationship with chlorophyll-a in the bay (R^2 =0.78) (Figure 4.1). The site-specific relationship between the chlorophyll-a and TP concentrations in the bay showed a strong but nearly uniform relationship (R^2 =0.68–0.92) (Figure 4.2). A similar, but stronger relationship was found between nitrate and chlorophyll-a concentrations for the sites in the bay (R^2 =0.59–0.96) (Figure 4.2). There was a stronger relationship between the Chl-a and TP levels (R^2 = 0.72) compared with nitrate (R^2 =0.59) for the control site.

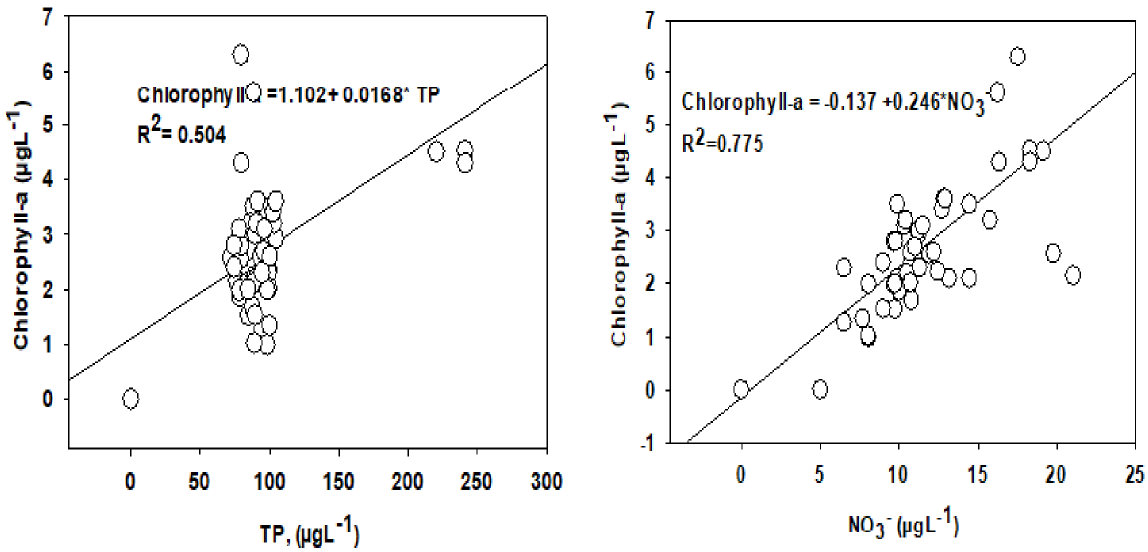

Figure 4.1: Relationship between Chlorophyll-a, total Phosphorus (TP) and Nitrates (NO3-) for all cage sites combined in the Kadimo Bay of Lake, Victoria, Kenya, data from January to October 2021.

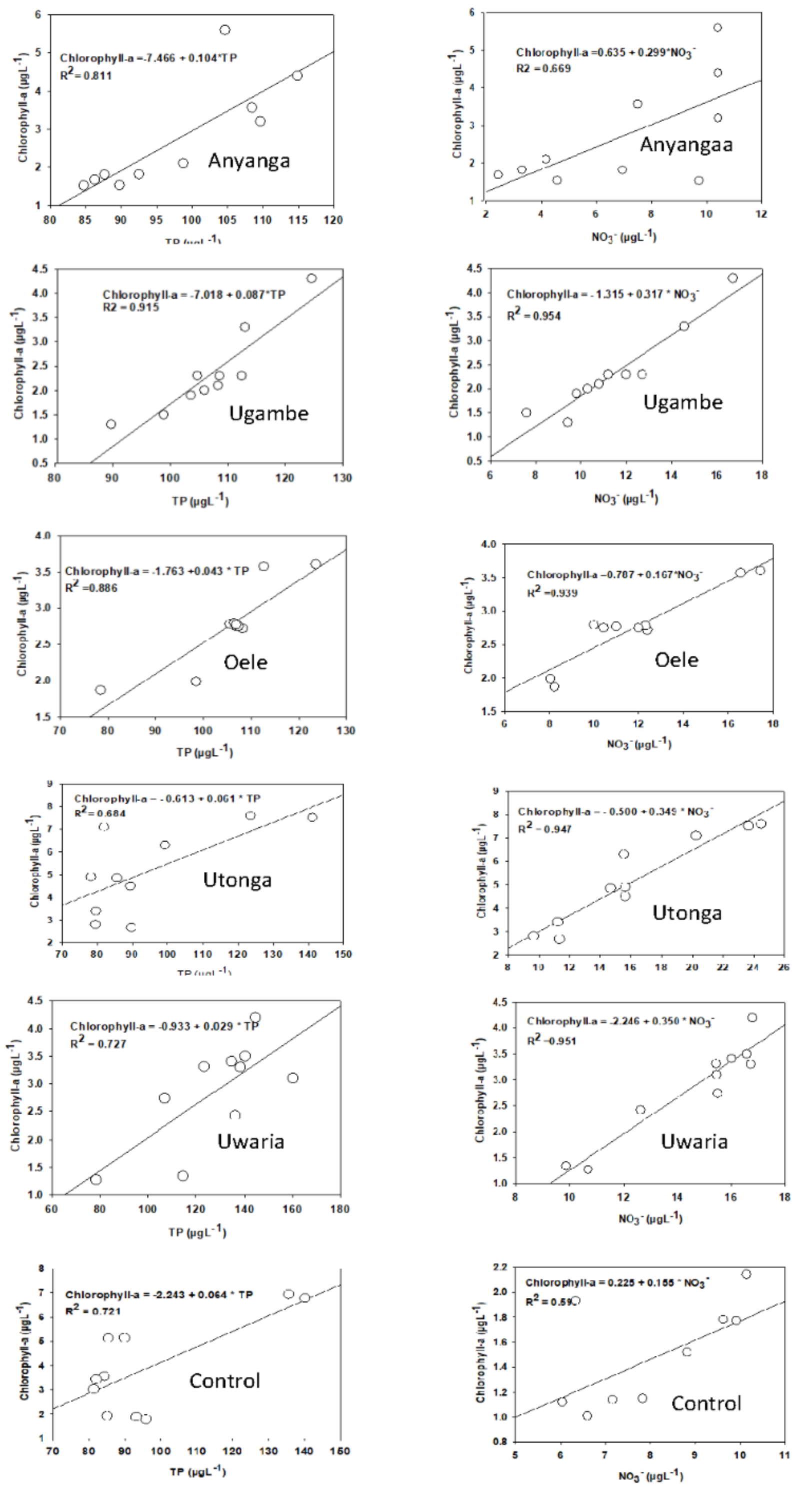

Figure 4.2: Site specific relationship between Chlorophyll-a, total Phosphorus (TP) and Nitrates (NO3-) in the Kadimo Bay of Lake, Victoria, Kenya, data from January to October 2021.

4.1.5 TN: TP Ratios

The TN concentration (mean ± SD) ranged from a minimum of 276.17 ± 54.64 μg/L at the Uwaria site to a maximum of 353.69 ± 26.98 μg/L at the Ugambe site (Table 4.5), while the TP concentration was lowest at the Utonga site (85.11 ± 10.51 μg/L) and highest at the Uwaria site (140.02 ± 24.43 μg/L; Table 4.5). The TN: TP ratio (a measure of nutrient limitation on primary production) ranged from a minimum of 1.97 at the Uwaria site to a maximum of 3.93 at the Utonga site, suggesting a strong limitation of TN, rather than TP (TN:TP < 10), in the bay.

Table 4.5: Mean (±SD) concentrations of total nitrogen (TN) and total phosphorus (TP) at cage and control sites in the Kadimo Bay, Lake Victoria, Kenya. TN limitation is considered probable when molar TN: TP < 10 and TP limitation when TN: TP > 20 (Maberly *et al*., 2020).

SITE	TN(μgL^{-1})	TP(μgL^{-1})	TN:TP	Limitation
Anyanga	332.92±27.22	86.53±2.37	3.85	Nitrogen
Uwaria	276.17±54.64	140.02±74.43	1.97	Nitrogen
Oele	339.82±34.75	92.94±8.79	3.66	Nitrogen
Ugambe	353.69±26.98	93.01±9.82	3.82	Nitrogen
Utonga	334.12±16.37	85.11±10.51	3.93	Nitrogen
Control	312.14±12.34	83.15±7.32	3.75	Nitrogen

4.2 Objective 2 and 3: Phosphorous assimilation load and fish production carrying capacity of fish cage sites in Lake Victoria, Kenya.

The estimated TP assimilation load of cage sites, the TP released by the current fish production, the maximum potential fish production and the current fish production are shown in Table 4.6. The estimated cage site maximum fish production potential within the Kadimo Bay (Table 4.6) ranged from a minimum of 0.307 MT year^{-1} at the Ugambe site to a maximum of 102.42 MT year at the Anyanga site showing variations in production potential at small spatial-scales. The other sites also had variable fish production potential that varied from a relatively high yield at Uwaria (72.03 MT year^{-1}), to low values for Utonga (6.48 MT year^{-1}), Ugambe (0.31 MT year^{-1}), and Oele (0.88 MT year^{-1}). The estimated potential maximum fish production for all the five cage sites were orders of magnitude lower than the current harvests by the farmers (Table 4.6).

The estimated TP released to the environment by current fish production (Pe) x current fish production) is greater than the TP that can be accommodated by sites (Lfish) for all the sites, indicating that the TP assimilation load at the cage sites has likely been exceeded (Table 4.6). Hence, the potential for more fish production at the cage sites in the Kadimo Bay, including the TP that can be accommodated by these cages sites (Lfish), indicates that both the maximum potential fish production and TP assimilation load for the bay have been exceeded (Table 4.6). The TP released by current fish production in the Kadimo Bay (Table 4.6) is a lot more than the TP that can be accommodated by the bay. The current cage fish production in the Kadimo Bay (Table 4.6) is therefore above the estimated maximum potential cage fish production of the bay following the mass-balanced model used in this thesis.

Table 4.6: Site TP Assimilation load, TP release by current fish production, maximum potential fish production and current fish production of cage sites in the Kadimo Bay, Lake Victoria, Kenya.

Site	Site TP Assimilation load (kg/year)	TP released by current fish production (kg/year)	Maximum potential fish production (ton/year)	Current fish production (ton/year)
Anyanga	2,760.270	170,324	102.420	6,320
Oele	23.761	113,190	0.882	4,200
Ugambe	8.279	32,340	0.307	1,200
Utonga	174.586	6,468	6.478	240
Uwaria	1,941.191	21,560	72.029	800
Kadimu Bay	4,949.241	343,882	183.645	12,760

4.3 Objective 4: Effect of stocking density on the growth performance and survival of the Nile tilapia (*O.niloticus)* in experimental cages at Anyanga cage site, Lake Victoria, Kenya.

4.3.1 Water quality variables for fish growth

Water quality variables did not differ significantly between the treatments (Table 4.7). However, mean (± SD) for pH ranged from a minimum of 7.6 ± 0.19 in treatment D125 to a maximum of 8.9 ± 0.13 in treatment D50. Dissolved Oxygen (DO) ranged from a minimum of 6.4 ± 0.38 mg L^{-1} in treatment D150 to a maximum of 7.5 ± 0.08 mg L^{-1} in treatment D75. Turbidity, a measure of sedimentation, varied from a minimum of 2.2 ± 0.53fmu in treatment D50 to a maximum of 4.9 ± 0.36fmu in treatment D150 (Table 4.7). Conductivity varied from a minimum of 103.9 ± 6.09 µS cm^{-1} in treatment D50 to a maximum of 107.5 ± 5.91 µS cm^{-1} in treatment D150, nitrates ranged from a minimum of 5.0 ± 2.44 mg L^{-1} in treatment D50 to a maximum of 7.8 ±2.71 mg L^{-1} in treatment D150, Nitrites ranged from a minimum of 0.1 ± 2.02 mg L^{-1} in treatment D50 to a maximum of

0.3 ± 1.48 mg L^{-1} in treatment D150 and ammonia ranged from a minimum of 0.5 ± 0.37 mg L^{-1} in treatment D50 to a maximum of 0.6 ± 3.83 mg L^{-1} in treatment D15O (Table 4.7).

Table 4.7: Variation of water quality variables in the different density treatments in the cage culture of the Nile tilapia in Lake Victoria, Kenya (mean ± SD).

	Stocking Density/ Treatments					ANOVA	
Parameters	D50	D75	D100	D125	D150	F	P
Temp. (°C)	26.5 ± 0.14	26.8 ± 0.12	27.5 ± 0.18	27.6 ± 0.18	27.7 ± 0.14	0.28	0.82
pH	8.9 ± 0.13	7.7 ± 0.25	8.1 ± 0.13	7.6 ± 0.19	8.0 ± 0.11	0.74	0.33
DO (mg/L)	7.3 ± 0.48	7.5 ± 0.08	7.2 ± 0.23	6.6 ± 0.56	6.4 ± 0.38	0.42	0.63
Turb. (fmu)	2.2 ± 0.53	2.9 ± 0.79	3.6 ± 0.83	3.7 ± 0.17	4.9 ± 0.36	0.25	0.84
Cond. (µs/cm)	103.9 ± 6.09	107.3±5.91	105.0 ± 6.29	107.3 ± 1.97	107.5±5.91	8.83	0.46
TDS(ppm)	62.0 ± 5.92	59.6 ± 1.60	65.9 ± 7.08	56.4 ± 1.85	67.5 ± 0.61	1.34	0.4
NO_3^-(mg/L)	5.0 ± 2.44	6.3 ± 3.82	6.6 ± 4.08	7.2 ± 4.34	7.8 ± 2.71	2.86	0.1
NO_2^-(mg/L)	0.1 ± 2.02	0.2 ± 2.04	0.2 ± 2.36	0.2 ± 1.29	0.3 ± 1.48	4.87	0.56
NH_3(mg/L)	0.5 ± 0.37	0.5 ± 0.90	0.5 ± 3.88	0.5 ± 3.84	0.6 ± 3.83	0.06	0.93

4.3.2 Growth and survival of the Nile tilapia in cages

The growth parameters: mean final weight (g), weight gain (g), average daily weight gain (g), specific growth rate % per day, survival rate %, feed conversion ratio and fish production (kg) of *O. niloticus* in varying density treatments are presented in Table 4.8. The mean (± SD) initial weight (5.5 ± 1.72 g) of the fingerlings did not vary among all treatments, while the final mean weight varied significantly among treatments (Table 4.8). The final mean weight (g) after eight months of the experiment varied from a minimum of 253.8 ± 10.64 g in treatment D125 to a maximum of 550.5 ± 15.81 g in treatment D50. The mean initial length was uniform (6.8 ± 0.63cm) among all treatments, while the mean final length varied significantly among treatments. The mean final length varied from a minimum of 17.9 ± 1.20 cm in treatment D150 to a maximum of 29.6 ± 3.59 cm in treatment D50 (Table 4.8).

The weight gain (g) varied from a minimum of 248.3 ± 10.64 g in treatment D125 to a maximum of 545.0 ± 15.81 g in treatment D50, while the average daily weight gain (g) ranged from a minimum of 1.0 ± 1.08 g in treatment D125 to a maximum of 2.3 ± 2.14 g in treatment D50. The specific growth rate (% per day) varied from a minimum of 1.6 ± 0.47% and 1.6 ± 0.30 in treatments D125 and D150, respectively, to a maximum of 1.9 ± 0.23 % and 1.9 ± 0.21 % equal growth rate in treatment D50 and D75, respectively. The survival rate at the end of the culture period was maximum (96%) for treatment D50 and minimum (79%) for treatment D150, while feed conversion ratio was minimum (1.2 ± 0.02) in treatment D50 and maximum (2.9 ± 2.01) in treatment D150. The fish production (kg) for the 240 days, was highest in treatment D75 at 32.9 ± 7.82 kg and lowest in treatment D125 at 26.9 ± 5.78 kg (Table 4.8).

Table 4.8: Growth performance parameters and survival rate of the Nile tilapia (*Orechromis Niloticus*) in experimental cages under different density treatments in Kadimo Bay Lake Victoria, Kenya.

Parameters	Stocking Densities/ Treatments				
	D50	D75	D100	D125	D150
Mean Initial Weight (g)	5.5 ± 1.72[a]	5.5 ± 1.72[a]	5.5 ± 1.72[a]	5.5 ± 1.72[a]	5.5 ± 1.72[a]
Mean final Weight (g)	550.5 ± 15.81[a]	532.9 ± 13.80[a]	353.7 ± 11.48[b]	253.8 ± 10.64[c]	258.5 ± 10.04[c]
Mean Initial Length (cm)	6.8 ± 0.63[a]	6.8 ± 0.63[a]	6.8 ± 0.63[a]	6.8 ± 0.63[a]	6.8 ± 0.63[a]
Mean final Length (cm)	29.6 ± 3.59[a]	28.9 ± 2.36[a]	24.5± 2.95[b]	22.5 ± 3.16[c]	17.9 ± 1.20[b]
Weight gain (g)	545.0 ± 15.81[a]	527.4 ± 13.80[a]	348.2 ± 11.48[b]	248.3 ± 10.64[c]	253.0 ± 10.04[c]
Average daily weight gain (g)	2.3 ± 2.14[a]	2.2 ± 2.13[a]	1.5 ± 1.22[b]	1.0 ± 1.08[b]	1.1 ± 2.06[b]
Specific Growth Rate (%)	1.9 ± 0.23[a]	1.9 ± 0.21[a]	1.7 ± 0.20[b]	1.6 ± 0.47[c]	1.6 ± 0.30[c]
Feed Conversion Ratio	1.2 ± 0.02[d]	1.3 ±1.02[c]	1.9 ± 2.01[b]	2.8 ± 1.33[a]	2.9 ±2.01[a]
Survival rate (%)	96	84	91	85	79
Fish production (kg/cage/240days)	27.2 ± 8.21[b]	32.9 ± 7.82[a]	28.3 ± 6.72[b]	26.9 ± 5.78[c]	31.3 ± 6.96[a]

4.3.3 Variability in fish condition among the cages

Condition factor (terminal), which define fish growth as influenced by the feed and the environment was highest in treatment D50 at 2.6 ± 2.83 and lowest in D150 at 1.8 ± 3.42 (Figure 4.3). The Turkey *post hoc* test revealed no significant difference ($p > 0.05$) in fish condition between treatment D50 and D75 as was between treatment D125 and D150 but there was significant difference ($p < 0.05$) between treatment D100 and the other treatments (Figure 4.3).

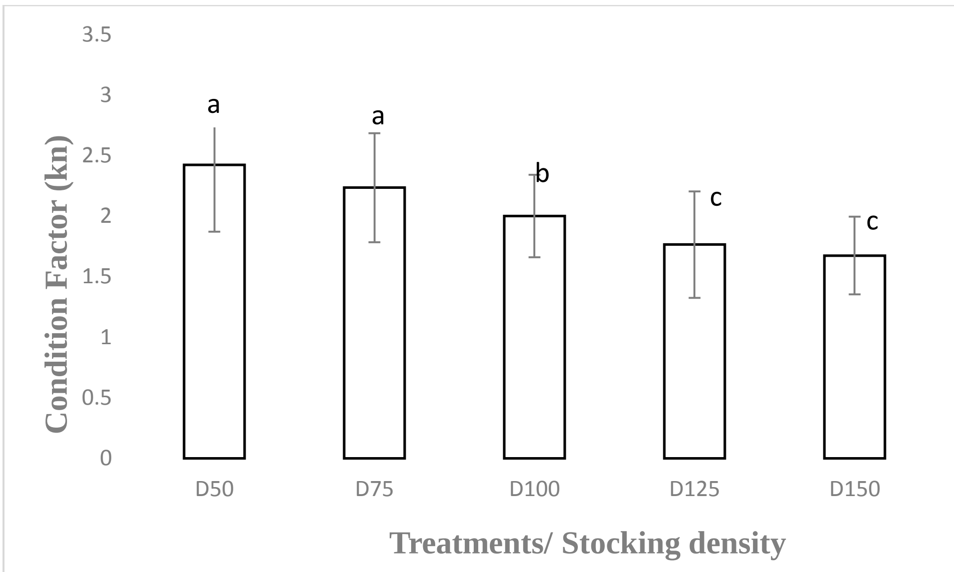

Figure 4.3: Variation of relative condition factor of fish cultured under different stocking densities in cages within Lake Victoria, Kenya. Error bars indicate SD, while similar letters indicate treatments with similar condition factor (P > 0.05).

4.3.4 Weight increments

The weight increments did not vary much among treatments for the first 60 days but exhibited clear variations from the 70th day of the experiment and towards the end of the experiment (Figure 4.4). Weight increment was highest in treatment D50 being 400g at the end of experiment at day 240. Treatment D75 had the second-best weight increment at 320.78g at the end of the experiment. Treatments D100, D125 and D150 had mean weight increment values that were close and ranged from 200 g to 250 g at the end of the experiment (Figure 4.4).

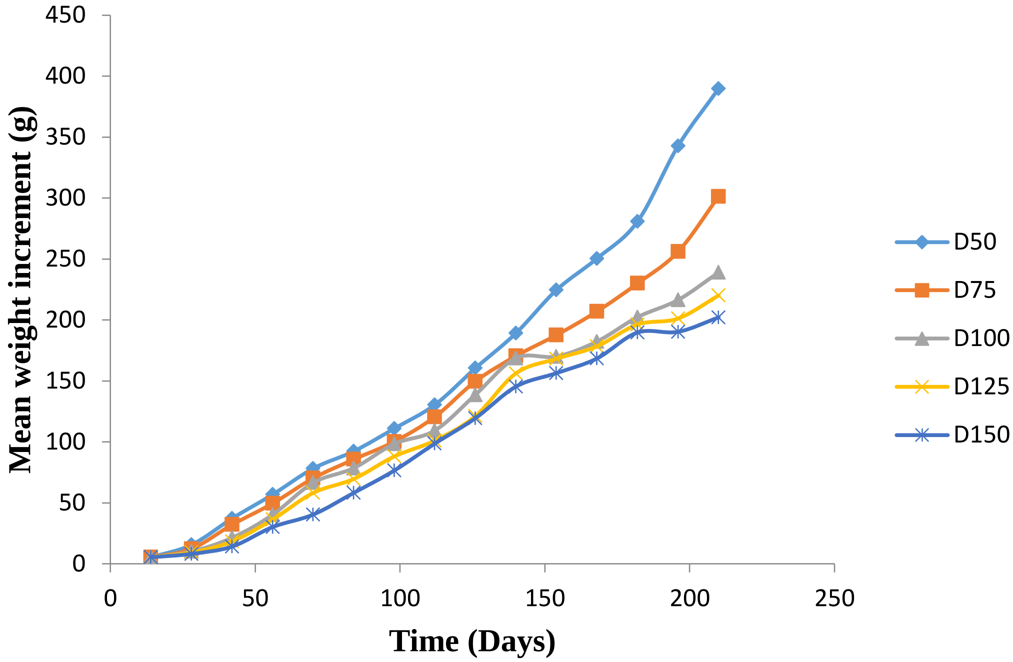

Figure 4.4: Variations in weight increment of cultured Nile tilapia (*O. niloticus*) under different stocking densities in experimental cages in Kadimo Bay Lake Victoria, Kenya, D50-D150 indicate stocking densities.

4.3.5 Economic Analysis of production

Considering the Cost-Benefit analysis for one production cycle, the total cost of production for one kg of fish for treatment (D50) was lower than the cost for the other treatments (D75, D100, D125 and D150) (Table 4.9). The total cost of production was highest for treatment (D150) and intermediate for treatment (D100). The total cost of production for one kg of fish tends to increase with increasing stocking density, while the profit margins decreased with increasing stocking density (Table 4.9). The profit margin was highest for treatment (D50) and intermediate for treatment D100 but negative for treatment D125 and D150 respectively within one production cycle. The Cost-benefit ratio was least for D50 at 0.48 and highest for D150 at 1.16 (Table 4.9), implying D50 is more cost effective for the production of one kg of fish than the other treatments.

Table 4.9: Cost-Benefit analysis of the Nile tilapia (*O. niloticus*) at different stocking densities in cages (12 m^3) after 240 days of culture within, Kadimo Bay, Lake Victoria, Kenya.

ECONOMIC ANALYSIS					
Parameters	D50	D75	D100	D125	D150
FCR	1.2	1.3	1.9	2.8	2.9
Cost of feed per kg (Ksh)	120	120	120	120	120
Cost of fish production per kg (Ksh)	144	156	228	336	348
Cost of fish sale per kg (Ksh)	300	300	300	300	300
Profit margin per kg (Ksh)	156	144	72	-36	-48
Cost-benefit ratio per kg of fish	0.48	0.52	0.76	1.12	1.16

CHAPTER FIVE

DISCUSSION

5.1 Determination of the influence of cage farming on water quality and trophic status of cage sites in Lake Victoria, Kenya

5.1.1 Water quality variables and standard limits for fish production

This study evaluated water quality and trophic states of fish cage sites in Kadimo Bay, Lake Victoria (Kenya), in order to generate information that can be applied for sustainable aquaculture production and development in the lake. Nearly all the water quality variables showed no significant differences ($p > 0.05$) between cage sites except for chlorophyll-a, conductivity and nitrites. The variables were highest at the cage sites for nitrites, conductivity and chlorophyll-a relative to the Control area that had no cages, suggesting influence of cage aquaculture on productivity and water quality in the bay. The nutrients from the fish feeds likely enhanced productivity and conductivity (an indirect measure of pollution) in the bay (Pillay, 2005). Although the bay is evaluated as being of light eutrophic state by this study, increasing levels of conductivity and algal biomass (measured by Chl-a) suggests possibility of the bay tipping over to eutrophication effects in the absence of regular monitoring plans (Gikuma-Njuru *et al*., 2021). As the three variables (Chloropyll-a, nitrite and electrical conductivity) are important for ecosystem metabolism (Hu *et al*., 2015), there is need for a more holistic management of the lake that integrates watershed management and aquaculture production (Musinguzi *et al*., 2019). Other studies, for example, Koldings *et al.* (2008) have controversially suggested eutrophication to be a more important challenge to Lake

Victoria fisheries more than overfishing. However, eutrophication threats are likely to be area and season-specific and to depend on depth profiles, watershed management and perhaps intensity of cage aquaculture in the lake.

Dissolved oxygen (DO) concentrations for all the cage sites were higher than the recommended minimum standard limit of 6 mg L^{-1} for aquatic life (APHA, 2005; Rodier *et al*., 2009) suggesting adequate aeration and perhaps little influence by decomposing feeds on DO levels. Decomposition of left-over feeds and wastes can lead to excessive deoxygenation of the water column with negative consequences such as fish kills or reduced benthic biodiversity (Beveridge, 1984). Many of the water quality parameters at the sites such as; acidity, total dissolved solids, turbidity, electrical conductivity, total suspended solids, nitrates, nitrites, total nitrogen, ammonia and ammonium ion concentrations were within the recommended standard limit for aquatic life, indicating less influence of the aquaculture activities on the ionic composition of the water and likely on ecological functioning of the bay. Similar findings have been reported for cage fish farming on the Tanzanian side of Lake Victoria and were attributed to water movements (Kashindye *et al*., 2015). The cage sites in Kadimo Bay had significantly lower values for some parameters (TDS & DO) and higher for others (EC, Turbidity, Nitrites, Total Nitrogen, Total Phosphorus, Ammonia & Ammonium ions) in relation to the Control site suggesting potential influence of caging on these parameters if tipping points are passed (Degefu *et al*., 2021; Gikuma-Njuru *et al*., 2021) and hence the need for regular monitoring of environmental quality changes.

5.1.2 Trophic state of the cage sites

The derived CTSI values indicated a light eutrophic state of the lake water around the cage sites, implying eutrophication is not currently a major threat to fish cage aquaculture in the bay. The same trophic state was found at the Control site suggesting a bay-wide trophic state that may not be solely attributable to the cage activities. The TP contributed most to the CTSI values followed by Secci depth, a measure of turbidity. This implies the need to monitor TP inputs into the bay and to prevent a possible phase shift to algal blooms with its many consequences (Masser, 2008). According to Mahmuti *et al*. (2019), the trophic states from light to medium eutrophic are not a threat to aquatic metabolism, however, it indicates a possibility of tipping over to eutrophic-hypereutrophic states as nutrient loading in the lake increases. Consequently, there is need for continuous monitoring of the water quality parameters of the cage sites in order to sustain aquaculture production and ecosystem functioning (Masser, 2008). This is particularly important as the intensity of the eutrophic state varies between months indicating potential role of other drivers such as rainfall and agricultural run-off on the water quality of the bay.

5.1.3 TN: TP Ratios

The TN: TP load for the bay suggests a nitrogen limitation of the water as the ratio is < 10 (Marbely *et al*., 2020). This finding is similar to the recent results obtained in other shallow Kenyan lakes such as Lake Baringo (Walumona *et al*., 2021) suggesting a likely stronger limitation of nitrogen compared to TP for Kenyan freshwater bodies. However, this notion will require more investigations. Although most freshwater lakes are limited by TP than nitrogen (Talling1966; Xie *et al*., 2003; Schindler, 2012) including reports for

Lake Victoria (Mugidde *et al*., 2005), there has been evidence of N limitation in some freshwater bodies (Elser *et al*., 1990; Sterner, 2008), prompting debates on the use of Volleinweider's signal-response TP models to manage eutrophication in lakes (Volleiweider, 1968; Sterner, 2008). Additionally, it has been argued as to which of the two nutrients (TP &TN) should be regulated or monitored, with some suggesting only the control of P is needed as cyanobacteria will fix N to reduce its limitation (Wurtsbaugh *et al*., 2019). However, TP control alone has been questioned (Glibert, 2017; Lewis and Wurtsbaug, 2008; Paerl *et al*., 2016) especially in lake basins with intensive agricultural run-offs that may supply TP, thus making it less limiting. The high concentration of TP in the bay and especially at Uwaria site and the potential for co-limitation of the nutrients will need further investigations. A more holistic integrated lake basin management approach (Kira, 1988) may be required to manage the lake environment.

5.1.4 Relationship between chlorophyll-a, total phosphorus (TP) and nitrates

The relationship between chlorophyll-a, TP and nitrates loads for all sites combined suggested a positive linear relationship that was stronger for nitrates than TP supporting the notion of nitrogen limitation in the lake. It is likely that fish wastes and excess feeds from the cages in addition to agricultural loading from the watershed, supplies the TP requirements for phytoplankton growth in the bay thus reducing the TP limitation effects (Xie *et al*., 2003). Nitrogen limitation can be maintained if TP is supplied to the lake in stoichiometric excess of N (including N fixation) and when Nitrogen fixation is inhibited by water column nitrates (Sterner, 2008). However, the exact reasons for the nitrogen limitation will require more investigations. Other studies in the same area have found the cages to have exceeded their TP carrying capacity (Sellu Mawundu unpubl. data), while some studies have found levels of TP in parts of the lake to be below the eutrophication thresholds (Kashindye *et al*., 2015; Gikuma-Njuru *et al*., 2021). Studies on nutrient loading in the lake have not found TP based eutrophication perhaps due to high flushing rates or rainfall dilution (Chamber *et al*., 2012; David *et al*., 2015; Kashindye *et al*., 2015; Yan *et al*., 2017). Recent studies show that primary production is nitrogen limited at N: P ratio <14 and phosphorus limited at N: P ratio >16 with co-limitation between the two thresholds (Yan *et al*., 2017). The lack of TP limitation and the light eutrophic state of the sites indicates the supply of TP to the bay need to be controlled through large-scale watershed management measures (Schindler, 1971) and through the control of fish cage feeding activities.

5.2 Phosphorous assimilation load and fish production carrying capacity of fish cage sites in Lake Victoria, Kenya.

The use of nutrient analysis, especially TP, in setting the limit of aquaculture production in African lakes and reservoirs is a call for policy development towards sustainable cage culture management. The mass-balance model provides a useful and heuristic tool for managing cage aquaculture in lakes and reservoirs (Pulatsu, 2003; David *et al.*, 2015). However, the accuracy of the TP based mass-balanced model applied in this study, will depend on the availability of accurate and recent data on the water balance parameters of aquatic systems, something which is lacking for most African lakes and reservoirs (Roberts & Zohary, 2018; Plisnier *et al*., 2022). This study applied historical water balance data for the Winam Gulf of Lake Victoria due to the unavailability of recent datasets. The estimates provided in this study especially on the flushing rates, will therefore require validation as more physical and limnological data becomes available on

Lake Victoria. Nonetheless, the study has delved into methodological and computational details to allow replication of the method as a policy tool for managing aquaculture in the African Great lakes and reservoirs.

The estimated allowable TP level for the studied bay is exceeded by the current TP released into the environment as a result of aquaculture activities. Excess TP can lead into increased algal biomass production through eutrophication (Pillay, 2008) and water quality deterioration. Some studies on the Winam Gulf have found TP levels not to have reached the eutrophication thresholds (Gikumu-Njuru *et al*., 2021) except for occasional seasonal increase in TP loading caused by agricultural run-off leading to localized eutrophication (Ledang *et al*., 2020). TP levels in this study ranged between 85.11 and 140.02 mg m^{-3} and are comparable to those of other studies in Lake Victoria (Gikuma-Njuru *et al*., 2021) and provided a moderate eutrophic state (Sellu unpublished data). However, human activities including deforestation, urbanization and agricultural production have the potential to increase nutrient load into Lake Victoria (Ogutu-Ohwayo, 1990; Roberts & Zohary, 2018) and could exacerbate the enrichment caused by aquaculture in the lake.

The maximum TP assimilation load for the studied sites has a direct correlation with the depth, flushing rates and allowable TP as per the mass-balanced model (*sensu* Dillon & Rigler, 1975). Except for the depth variable, the other parameters will require more validation in future studies. For example, the accuracy of TP allocation load (Δ [P]) based on maximum TP concentration of 100 mg m^{-3} (Aura, 2020) will affect the maximum TP an area can hold from aquaculture and the potential fish production based on the model. The maximum allowable TP value in lakes varies between jurisdictions with a recorded maximum of 300 mg m^{-3} in some waters (Pulatsu, 2003) and low values of up to 30 mg m^3 in reservoirs (David *et al.*, 2015). There is no clear policy on the maximum allowable TP values in Lake Victoria and hence requiring more validation of the proposals by KMFRI (Aura, 2020) in future studies.

The TP based mass-balanced model used in this study suggests the TP assimilation load (4,949.2kg $year^{-1}$) and maximum potential fish production (183.65 tons $year^{-1}$) for the cage sites in the bay have been surpassed by the current fish production in the bay of (12,760.0 tons $year^{-1}$). These estimates are based on a precautionary approach but are useful starting guidelines for the management of Lake Vitoria cage aquaculture. There has not been a clear policy guideline on the number of cages allowed in Lake Victoria, leading to conflict between the cage fish farmers and wild stock fisheries (Njiru *et al*., 2018). Determination of carrying capacities for fish production and TP loads in the lake's shallow bays is important for a planned cage aquaculture enterprise including the setting up of sites for "aquaculture parks" (*sensu* David *et al*., 2015). TP addition by the cage aquaculture in the lake is likely to synergize with run-off inputs from agricultural activities around the lake hence the novelty of precautionary approach used to estimate TP allocation levels in this study and others (David *et al*., 2015; Mahamudi, 2019).

5.3 Effect of stocking density on the growth performance and survival of the Nile tilapia (*O.niloticus)* in experimental cage Lake Victoria, Kenya.

In this study, the water quality variables were within optimal range for tilapia growth throughout the experimental period. The variation of water temperature (26.53 - 27.74°C) for example, was within recommended ranges for tilapia growth (Moniruzzaman *et al*., 2015). For optimum fish growth, dissolve oxygen levels should be higher than 5ppm for warm water fishes (Body, 1982; Lucas *et al.*, 2019). All the nutrients (Nitrates and nitrites) were within the recommended range for the growth of tilapia (Boyd 1982; Lucas *et al*., 2019) indicating that water quality at the experimental site did not confound the growth of the fish.

Analysis of the influence of stocking density on the growth and survival of *O. niloticus* revealed that, growth performance as measured by weight gain was not significantly different between treatment D50 and D75 but significantly higher than treatment D125, D150 and D100. Treatments D125 and D150 showed no significant difference in growth. However, there was a significantly lower growth in treatment D100 (which was used as the control) than the four other treatments D50, D75, D125 and D150. Even though there was no significant difference in terms of weight gain between treatment D50 and D75, fish production (kg) was highest in treatment D75, compared to other treatments. These findings support the work of others (Kawamoto, 1957; Haque *et al*., 1984) who have suggested that growth in fish is best at lower stocking densities. The reasons for the better growth performance in the lower treatment D50 can be associated with reduced competition for space, food and reduced crowding stress. The growth performance of *O. niloticus* will vary spatially and geographically in relation to differences in the growth environment, requiring determination of the optimum stocking densities in different water bodies (Moniruzzaman *et al*., 2015). Variations in growth performance in relation to stocking densities have been reported by different studies (Sayeed *et al*., 2008; Asase, 2013) with consistent higher growth at lower densities but variable optimum densities for optimum economic returns. Percentage survival rate for this study were 79%, 85%, 91%, 84% and 96% for D150, D125, D100, D75 and D50, respectively. These findings are comparable with the results from other tropical ecosystems where fish cage farming has been applied (Sayeed *et al*., 2008). The survival rate decreased with increasing stocking density probably due to increasing competition for space, oxygen and food among individual fish. The treatments with the best growth performance (D50 and D75) showed highest survival rates indicating the interaction between optimum growth and survival for viability of aquaculture facilities.

Economic analysis on the cost of fish production per kg of fish showed an increase in the cost of production with increasing stocking densities of the tilapia. From the analysis done on one production cycle, stocking at D50 provided the best economic performance with the best Cost-Benefit ratio of 0.48, while D150 provided the worst Cost-Benefit ratio of 1.16, for one production cycle, and is likely to decrease in subsequent production cycles as a result of reduced cost of fish production per kg of fish.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

Most of the water quality variables are not significantly different between cage sites and the Control site with the exception of chlorophyll-a, conductivity and nitrites. The result of this study evaluated the bay as being of light eutrophic state. There is apparent need for a holistic management of the bay that takes into account activities in the catchments and within the lake. Eutrophication threats in the bay are likely to be area or season specific. Dissolved oxygen concentration around the cage sites in the bay are above the recommended threshold limit for aquatic life suggesting that decomposing fish feeds are not a threat to the oxygen tension in the water. The other water quality variables are within the recommended threshold standards for aquatic life indicating lack of significant influence of cage aquaculture on the water but calls for the need not to surpass the tipping points. The relationship between chlorophyll-a total phosphorus (TP) and nitrates suggest a positive linear relationship that is stronger for nitrates than TP.

Based on the CTSI results, the cage sites in the bay are at the stage of light eutrophic state, meaning eutrophication is not a current threat to fish cage culture. TP concentration account largely for the CTSI values with Secchi disk reading ranking second. The TN: TP ratio suggest nitrogen limitation of the bay. The TN and TP loading needs to be monitored to prevent the conditions tipping over to high eutrophic state. A number of physico-chemical variables were found not to be different between the cages and Control sites indicating lack of significant influence of the cages on water quality. The cause of apparent TN limitation in the bay will require further investigations to include seasonality and to extend to other bays of the lake situated in agricultural watersheds. The apparent prevalence of TN limitation in the bay should inform eutrophication control measures based on TN and potential TP co-limitation rather than TP loading alone as commonly practiced.

In attempting to investigate the amount of phosphorus released in to the lake and the amount the lake can assimilate, this study provides a pioneering policy tool for managing aquaculture development in Lake Victoria and other African water bodies for sustainable livelihoods and ecosystem functioning. The mass-balanced model outputs used in this study will require re-parameterization as more data become available but are an important starting guideline for science-based management of aquaculture in the lake. Scientific effort is therefore required in order to generate recent data on water balance parameters for the lake, in addition to other limnological variables necessary to fit the model.

The growth performance of the Nile tilapia was highest at stocking densities of D50 and D75 fish m^{-3}, implying lower stocking densities of tilapia will exhibit better growth performance and survival rate than higher stocking densities currently practiced. Fish production, was highest at D75 but the benefit-cost ratio was highest for fish stocked at D50, suggesting D50 to be the most suitable stocking density for cage fish farmers in the study area. It is therefore concluded that the Nile tilapia performed relatively better at a lower stocking density (50 fish m^{-3}) and, water quality did not affect the growth performance of the fish.

6.2. Recommendations

Following the results of this work, the following recommendations are made:

1. That relevant government agencies responsible for fisheries management should institute monitoring, control and surveillance (MCS) programs in order to continuously track the eutrophic state of the cage sites so as to avoid tipping over to a highly eutrophic state with consequent effects on the ecological services of the bays.
2. The recommended stocking density for *O. niloticus* cage culture at Anyanga cage site based on the results of this study is 50 fish m^{-3} for cage fish farming. This is twice the density being used presently by the farmers, and will lead into reduced cost-benefit outcomes and preserve the ecological integrity of the lake.
3. The Phosphorus assimilation load estimates provided in this study (4,949.2 kg $year^{-1}$) using the mass-balanced model, will require validation as more physical and limnological data becomes available on Lake Victoria. However, the model provides precautionary results useful for the quantification of phosphorus load in the lake.
4. The TN: TP ratio generated in this study suggest an apparent TN limitation in the bay. This limitation will require further investigations to include seasonality and should extend to other bays of the Lake that are located in agricultural watersheds.

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APPENDICES

Supplementary Material

Appendix I: Table S1 Two-way ANOVA results for 17 selected variables measured at aquaculture cage sites in the Kadimo Bay in Lake Victoria, Kenya, for the period January to October 2021. Bold figures depict variables with no significant effects between months or sites.

Variable	Source of Variation	DF	Adj ss	Adj MS	F-Value	P-Value
a) Temp.	Months	11	3.493	3.4931	2.97	**0.105**
	Site	5	1.075	0.2150	0.18	**0.965**
	Season*Site	5	2.243	0.4486	0.38	**0.854**
	Error	15	17.627	1.1752		
	Total	26	22.599			
b)pH	Months	11	0.204	0.2046	0.74	**0.403**
	Site	5	1.301	0.2602	0.94	**0.482**
	Season*Site	5	0.219	0.0438	0.16	**0.974**
	Error	15	4.141	0.2761		
	Total	26	5.803			
c)DO	Months	11	4.125	4.1254	3.06	**0.101**
	Site	5	2.501	0.5003	0.37	**0.861**
	Season*Site	5	8.335	1.6669	1.23	**0.341**
	Error	15	20.248	1.3498		
	Total	26	36.513			
d)TDS	Months	11	54.57	55.57	1.87	**0.192**
	Site	5	194.79	38.96	1.33	**0.303**
	Season*Site	5	53.68	10.74	0.37	**0.863**
	Error	15	437.94	29.20		
	Total	26	767.94			
e)Turbidity	Months	11	0.87	0.8739	0.24	**0.629**
	Site	5	4.59	0.9179	0.26	**0.930**
	Season*Site	5	1.32	0.2637	0.07	**0.995**
	Error	15	55.81	3.5870		
	Total	26	59.52			
f)Conductivity	Months	11	31.53	31.533	4.26	**0.057**
	Site	5	366.63	73.325	9.91	0.000
	Season*Site	5	30.19	6.038	0.82	**0.557**
	Error	15	111.01	7.400		
	Total	26	691.75			

g)TSS	Months	11	0.08	0.079	0.13	**0.724**
	Site	5	4.52	0.904	1.46	**0.259**
	Season*Site	5	5.56	1.113	1.80	**0.173**
	Error	15	9.26	0.617		
	Total	26	21.10			
h) POM	Months	11	0.21	0.214	0.18	**0.679**
	Site	5	0.70	0.140	1.17	**0.369**
	Season*Site	5	0.23	0.045	0.38	**0.855**
	Error	15	1.80	0.120		
	Total	26	2.67			
i)Chl-a	Months	11	5.04	5.042	0.45	**0.511**
	Site	5	265.21	53.040	4.78	0.008
	Season*Site	5	4.44	0.889	0.08	**0.994**
	Error	15	166.60	11.107		
	Total	26	439.55			
j)SRP	Months	11	3.31	3.306	0.05	**0.825**
	Site	5	326.40	65.279	1.01	**0.448**
	Season*Site	5	125.24	25.048	0.39	**0.851**
	Error	15	973.69	64.912		
	Total	26	1398.51			
k) NO_3^-	Months	11	10.51	10.505	1.15	**0.301**
	Site	5	120.17	24.035	2.63	**0.067**
	Season*Site	5	18.51	3.703	0.41	**0.838**
	Error	15	137.14	9.142		
	Total	26	287.16			
l)NO_2^-	Months	11	7.01	7.013	2.89	**0.110**
	Site	5	50.75	10.151	4.18	0.014
	Season*Site	5	13.58	2.708	1.12	**0.394**
	Error	15	36.42	2.428		
	Total	26	107.08			
m)NH_3	Months	11	336.22	336.216	3.04	**0.102**
	Site	5	19.07	3.814	0.03	**0.999**
	Season*Site	5	152.20	30.440	0.28	**0.920**
	Error	15	1658.89	110.593		
	Total	26	2346.94			
n)NH_4^+	Months	11	17.83	17.83	0.38	**0.547**
	Site	5	177.45	35.49	0.75	**0.596**
	Season*Site	5	126.06	25.21	0.54	**0.746**
	Error	15	705.95	47.06		
	Total	26	990.75			

o)TN	Months	11	311.0	311.0	0.16	**0.694**
	Site	5	18174.8	3635.0	1.88	**0.158**
	Season*Site	5	1175.7	235.1	0.12	**0.985**
	Error	15	29003.8	1933.6		
	Total	26	48432.7			
p)TP	Months	11	226.2	226.2	0.12	**0.731**
	Site	5	11978.9	2395.8	1.30	**0.315**
	Season*Site	5	1228.0	245.6	0.13	**0.982**
	Error	15	27609.8	1840.7		
	Total	26	40515.2			
q)SiO_4^{4-}	Months	11	0.03	0.028	0.00	**0.954**
	Site	5	11.05	2.211	0.27	**0.920**
	Season*Site	5	15.03	3.006	0.37	**0.860**
	Error	15	121.08	8.071		
	Total	26	156.63			

Appendix II: Table S2 Field sampling data for analysis on the influence of cage culture on water quality and trophic status of Lake Victoria; a case study of the Kadimo Bay and phosphorus assimilation load and production carrying capacity of cage sites in the Kadimo Bay

Date	sites	Temp (^{0}C)	PH	DO (mg/l	TDS (ppm)	Turbidity (fmu)	Conductivity (microsimen/cm	Salinity (psu)	ORP (mv)	Secchi disc (m)	**TSS (mg/L)**	**POM (mg/L)**	**Chlorophyll a (μgL^{-1})**	**SRP(μgL^{-1})**	**NO_3- (μgL^{-1})**	**NO_2- (μgL^{-1})**	**NH_3 (μgL^{-1})**	**Ammonium(μgL^{-1})**	**TN(μgL^{-1})**	**TP(μgL^{-1})**	**Silicate(mgL^{-1})**
Jan	Anyanga	27.27	7.92	7.49	68.9	1.8	110.1	0.05	-235.6	1.4	4.33	2.00	1.52	12.00	9.72	7.66	22.64	16.56	354.95	84.71	14.16
Jan	Uwaria	27.39	7.46	7.91	68.9	2	110.9	0.05	-213.4	1.6	3.17	1.50	17.52	37.00	13.50	8.00	14.40	41.56	211.20	241.20	16.48
Jan	Olele	27.69	7.56	8.23	69.9	1.5	111.6	0.05	-216.8	1.5	3.50	1.33	1.27	8.67	6.50	3.43	14.40	15.31	377.05	94.71	13.58
Feb	Ugambe	27.02	8.8	4.84	59.8	2.5	112.3	0.04	-312.3	1.6	5.50	2.00	2.92	28.67	10.65	5.38	18.52	29.06	388.11	104.71	15.76
Feb	Utonga	26.87	8.9	3.67	61.4	2.7	101.4	0.08	-298.2	1.5	4.33	1.33	3.57	15.33	9.78	4.34	14.11	12.18	348.63	71.86	7.76
Feb	Control	26.72	8.6	4.42	57.5	1.5	98	0.06	-299.7	1.8	4.17	1.50	4.15	23.67	1.02	0.65	20.58	20.93	353.37	76.14	16.63
Mar	Anyanga	27.78	7.45	7.8	69.55	1.9	112.3	0.05	-223.4	1.7	4.5	2.33	2.1	15.33	3.18	2.79	37.04	25.93	370.74	83.29	13.14
Mar	Uwaria	27.74	8.03	7.92	68.55	1.7	112.1	0.05	-221.3	1.5	5.67	2.33	14.5	30.33	9.14	6.41	43.21	27.81	213.48	220.45	17.65
Mar	Olele	27.71	7.59	7.74	69.34	1.8	111.6	0.05	-239.2	1.43	3.5	1.67	4.2	18.67	5.76	4.34	47.30	28.43	375.47	103.29	16.77
April	Ugambe	27.43	8.07	7.76	68.9	3.6	111	0.05	-312.2	1.8	4.23	2.31	1.69	16.72	9.78	4.56	20.34	17.12	346.78	87.56	13.45
April	Utonga	27.86	8.34	8.12	69.52	3.3	112	0.05	-275.7	1.5	3.45	1.72	1.87	9.87	8.23	5.48	21.22	18.42	344.25	78.45	14.44
April	Control	27.63	8.04	8.27	56.65	1.8	99	0.05	-282.7	1.6	3.36	1.65	2.23	12.45	1.01	0.76	23.42	16.25	353.26	89.23	13.42
June	Anyanga	26.67	7.99	7.43	67.45	3.5	111.3	0.5	-321.5	1.7	5.4	2.02	1.53	23.45	4.58	2.45	24.67	11.89	332.46	89.76	12.46
June	Uwaria	26.34	8.02	8.44	68.72	3.9	110.4	0.05	-299.8	1.3	4.6	1.99	12.56	22.22	11.23	4.48	22.45	15.67	348.65	79.56	14.24

June	Olele	26.57	8.24	6.78	69.44	3.6	112.4	0.05	-287.9	1.9	4.7	1.26	1.34	21.78	7.67	5.56	31.32	14.72	345.78	100.23	17.66
July	Ugambe	26.73	7.99	7.34	70.45	4.1	113.6	0.05	-278.8	1.6	6.5	1.87	2.36	10.56	10.72	6.75	23.16	18.12	365.47	99.86	18.09
July	Utonga	26.44	8.01	7.44	71.34	4.2	102.7	0.05	-312.4	1.8	4.3	2.44	1.99	12.78	8.05	4.35	25.24	19.34	336.89	98.47	15.46
July	Control	26.52	8.02	6.88	55.88	2.4	98.7	0.05	-276.5	1.4	3.2	2.31	1.02	13.45	1.03	0.98	22.36	21.09	358.74	89.23	13.44
Aug	Anyanga	25.4	7.41	5.78	56.34	5.4	106.7	0.05	-215.8	1.5	4.6	1.99	5.6	11.30	10.4	6.72	12.34	18.55	306.80	88.46	11.90
Aug	Uwaria	25.6	7.25	7.55	54.22	6.4	104.8	0.05	-217.4	1.7	5.3	2.01	6.3	10.40	7.52	7.45	14.24	17.98	304.72	79.42	14.35
Aug	Olele	25.3	7.32	8.23	58.76	5.2	109.6	0.05	-219.8	1.6	4.2	1.88	3.5	9.66	8.14	5.33	12.31	19.33	311.24	88.21	12.89
Sept	Ugambe	25.4	7.21	7.36	68.3	4.4	110.8	0.05	-220.6	1.7	5.4	1.77	4.3	11.20	9.11	5.43	13.45	17.87	314.42	79.89	16.44
Sept	Utonga	25.2	7.32	6.88	67.5	5.2	112.5	0.05	-212.4	1.5	4.3	1.68	3.6	10.60	8.34	6.28	12.66	19.66	306.71	91.67	17.43
Sept	Control	25.3	7.41	6.97	66.8	5.1	99.2	0.05	-215.3	1.4	5.2	1.76	2.4	10.50	11.42	5.55	12.68	15.47	305.32	74.56	10.55
Oct	Anyanga	25.2	7.45	6.78	67.77	5.4	110.7	0.05	-213.5	1.6	5.4	1.77	3.2	12.30	10.41	6.78	13.40	18.43	299.67	86.45	15.64
Oct	Uwaria	25.4	7.42	7.43	66.54	5.2	113.4	0.05	-215.6	1.5	5.7	1.68	2.8	11.40	9.65	6.02	12.60	17.88	302.82	79.46	12.36
Oct	Olele	26.3	7.56	6.35	68.43	5.3	112.5	0.05	-214.3	1.4	5.8	1.76	3.1	11.60	10.32	6.11	11.57	19.23	289.54	78.24	11.46
Nov	Ugambe	26.3	7.31	8.1	67.8	6.6	109.7	0.05	-216.7	1.6	5.3	1.65	4.4	9.99	8.99	7.66	12.22	18.88	300.01	87.99	15.26
Nov	Utonga	25.4	7.24	7.23	68.5	5.9	110.21	0.05	-214.8	1.5	5.7	1.72	5.3	11.23	11.24	6.88	14.78	17.68	297.56	76.45	11.46
Nov	Control	25.7	7.56	6.55	68.45	5.8	111.4	0.05	-216.2	1.8	4.9	1.74	3.9	11.21	10.44	5.74	11.28	19.22	299.99	77.89	13.98
Dec	Anyanga	25.4	7.33	7.49	68.46	5.4	113.6	0.05	-215.7	1.6	5.1	1.69	4.2	10.67	8.89	6.24	12.66	14.27	305.56	84.96	11.38
Dec	Uwaria	25.8	7.12	7.08	59.66	4.9	110.4	0.05	-218.3	1.9	4.8	1.66	4.8	10.54	9.22	7.23	11.89	15.68	308.24	79.45	14.29
Dec	Olele	25.3	7.45	7.21	63.44	5.6	112.7	0.05	-213.7	1.4	5.5	1.67	5.6	11.23	9.95	5.67	13.77	16.95	306.45	77.24	16.44

Appendix III: Table S3 Final field sampling data (Raw data) for analysis of growth performance and survival of tilapia (Oreochromis niloticua) in cage aquaculture at the Anyanga cage fish site, Kadimo Bay, Lake Victoria, Kenya.

A1		B1		C1		D1		E1		A2		B2		C2		D2		E2		A3		B3	
W	L	W	L	W	L	W	L	W	L	W	L	W	L	W	L	W	L	W	L	W	L	W	L
775	33	700	31	580	29.3	426	27.5	420	28.5	933	40	645	32	512	29	425	27.3	422	28.6	822	34.2	784	33
822	34	668	31.3	586	30	500	30.2	480	29	810	40	523	29	486	29	506	30.1	533	30.8	775	33	782	35
595	30.2	708	32	486	28.5	360	26.4	315	25.2	787	34	634	30.3	432	28.3	362	27	280	22.4	930	39.1	600	30.8
540	29.2	666	32.1	430	28.3	320	27	188	21.1	564	30	540	29.2	342	24.6	240	23	307	26.2	700	31.6	637	30.2
634	30.3	534	30	384	26.4	245	22.6	234	22.6	570	29.6	439	27	248	22.2	352	26.9	249	22.4	524	30	426	27.5
660	31.2	567	29	453	28.2	354	26	302	24.6	668	31	447	28.5	283	21.3	340	24.5	189	21.7	507	30	436	29.3
700	31	580	31	426	27.5	366	27	350	26.5	700	31	328	26	219	22.8	430	28.4	150	19.3	583	27.5	555	30.2
645	32	486	28.5	474	27.3	342	24.6	320	25.4	600	31	374	26.5	186	21.1	156	19.6	220	22.6	600	31	564	30
911	35	600	31.6	534	30	430	28.4	299	24.5	580	31	564	30	352	26.3	373	27	136	18.6	550	29	450	28.2
662	32	570	29.6	502	29.1	150	19.5	151	19.5	474	27.5	480	29	224	22.6	243	22.4	340	24.5	637	30.2	602	31.3
596	31	543	30	438	28	180	20.8	290	24.5	437	27	430	28.3	283	22.2	147	18.2	154	20.2	911	35.2	778	33.4
565	30.3	422	26.8	342	24.6	300	25	338	25.7	583	27.5	373	29	310	26.4	301	24.2	240	22.1	914	35	824	34.1
822	34	734	31	401	27	316	24.7	301	24.6	596	31	349	26	286	23.1	221	22.7	191	22.3	580	31	570	29.6
803	34	736	32.1	570	29.6	245	22.6	234	22.6	564	30	366	26.5	300	25	218	22.3	246	22.6	596	31.2	550	30
634	30.3	564	30	315	25.2	306	25.3	342	24.6	803	34	784	33	486	28.5	302	25.2	230	22.3	810	40	787	34
596	31	550	30.1	290	24.5	219	22.8	206	22.8	440	25.9	424	28	305	26.5	320	25.4	305	24.7	393	27	366	27
583	27.5	480	29	370	26.5	220	22.8	304	24.6	565	30.3	502	29.1	150	19.3	180	21.1	236	22.6	430	28.3	396	26.8
512	29	430	28.3	352	26.3	280	22.2	248	22.3	564	30	664	32	354	26	240	22.6	233	22.6	668	31	534	30.2
524	30	476	28.5	340	24.6	160	20.4	152	19.6	822	34	700	32.8	303	26	420	28.6	144	18.2	702	31	668	31.3
565	30.3	438	28	366	26.5	230	23	146	18.8	240	22.5	374	28.7	300	26	317	24.4	190	22.3	567	29.2	446	25.9
564	30	540	29.2	301	24.6	203	22.4	190	22.11	418	22.7	400	26.8	180	21.3	282	22.1	283	23.6	583	26.4	500	30.3
356	20.5	735	31.8	280	20.3	140	18.2	156	19.3	289	21.3	401	27	165	19.4	165	21.1	340	25.8	444	25.9	400	26.8
234	22.6	680	31.5	200	19.3	144	18.6	138	17.4	386	22.6	348	27	200	22	172	22	244	22.1	564	30	512	29.2

600	31	547	30	430	28.5	340	26.3	373	27	401	27	393	27	302	25.8	152	19.4	317	24.8	384	27.2	320	26.3
637	30.2	498	29	348	24.2	190	22	140	18.2	634	30.3	580	31	202	21.9	290	24.6	292	24.7	530	29.5	424	28.3
453	20.4	588	28.4	200	19.6	243	22.6	233	22.4	500	30.3	360	26.5	306	25.3	341	26.8	211	22.3	356	26.5	315	25.2
383	27	400	27.4	204	19.7	148	18.6	145	18.4	668	31	802	33.4	203	22.8	240	22.3	301	24.6	224	22.6	580	30.4
784	33	668	32.2	430	28.3	302	24.6	245	22.6	390	26.5	600	31.5	306	27.1	308	24.2	130	15.3	374	26.5	366	26.5
401	27	384	26.3	283	22.2	182	21.6	200	21.8	534	30	354	26	278	23.4	358	26.7	230	23.2	453	28.2	421	27.2
634	30.3	564	30	410	25.2	210	22.7	190	22.3	564	30	348	24.2	299	24.5	140	17.8	208	22.8	668	31	634	30.4
567	29	426	27	360	26.4	214	22.7	301	24.6	550	30	356	24.8	315	25.2	148	18.1	231	22.3	474	27.3	424	28
662	32	564	30	295	24.2	230	22.8	150	19.6	543	30	667	31	151	19.5	220	20.1	180	20.1	634	30.2	603	31
543	29.8	423	26.7	301	24.6	218	21.6	190	22.6	512	29	662	31.3	360	26.5	300	25.1	240	22.1	600	31.1	552	30.2
500	30.3	637	30	482	29.2	283	22.6	316	25.3	596	31	637	30.2	401	27	340	26.1	420	28.3	426	27.5	420	27.3
550	29.6	579	30	486	28.5	384	26.4	340	26.6	586	30.2	440	25.6	315	25.2	230	24.8	302	25.2	150	19.2	608	32
668	31	600	31	360	26.5	348	24.2	338	25.6	486	28.5	410	25.1	301	24.3	245	22.3	300	24.5	543	30.2	438	28.2
700	31	596	31	245	22.6	190	22	320	25.4	354	26	580	31	156	20.4	138	17.3	209	22.6	422	26.8	385	26.7
637	30.2	480	29.1	373	27	230	22.2	206	22.8	422	26.8	599	30	283	22.6	280	23.1	318	24.7	354	26	343	24.6
580	28.2	498	29	420	27.8	348	24.2	304	24.6	342	24.6	675	32	181	21.2	421	28.4	163	21.3	441	25.8	422	26.8
604	25	580	31	400	26.8	316	25.2	340	26.3	384	26.4	320	20.4	152	19.6	341	24.3	307	24.4	564	30	488	29.3
670	26	662	32	437	27	320	25.6	243	22.6	283	22.2	430	28.3	146	18.6	302	24.2	222	22.5	634	30.3	553	29.2
490	26.5	438	28	219	22.8	187	21.2	360	26.4	676	32	480	29	298	24.5	138	18.1	352	26.8	540	29.2	522	28.3
509	29	451	26.5	366	26.5	219	22.8	180	20.8	509	29	372	21.6	246	23.2	280	22.1	165	19.4	595	30.2	570	29.6
453	28.2	480	26.5	245	22.6	150	19.8	316	24.7	453	28.2	422	26.8	220	22.2	219	22.4	181	21.4	421	27.3	800	34
810	40	478	26	315	25.2	246	22.8	146	18.8	784	33	384	26.4	316	25.3	318	24.2	158	20.3	476	28.2	530	29.5
737	34	787	32.3	220	22.1	155	20.5	210	22.7	782	35	698	32.2	204	20.3	342	26.7	290	24.6	390	26.5	486	28.5
637	30	486	28.5	240	22.6	152	19.5	230	23.1	634	30.3	420	28.1	301	24.8	410	27.2	181	20.2	580	31	487	29.4
676	32	608	30	221	22.1	219	22.8	140	18.6	660	32.1	783	33.2	180	19.2	140	16.3	240	22.3	400	26.8	700	34.2
		780	31	420	27.2	303	24.6	142	18.8			780	33.8	182	19.3	212	22.4	143	18.1			502	29.1
		599	30	380	26.4	350	26.1	190	22.3			543	30.1	306	24.5	244	22.3	340	24.3			599	30
		486	28.5	390	27.3	348	24.2	233	22.2			315	25.2	220	22.4	341	24.6	431	28.6			420	28.2

560	27	246	22.1	316	24.7	219	22.4	360	26.4	225	22.3	180	21.2	280	22.1	570	29.4
637	30.2	348	23.2	245	22.6	139	17.6	366	26.5	228	22.9	120	14.3	136	17.8	544	30.2
700	31.2	356	26.5	354	26	141	18.3	709	34.4	299	24.5	132	15.4	188	21.3	596	30.3
550	30.2	342	24.6	366	27	320	25.6	788	34.2	151	19.5	142	17.3	170	22.2	426	27.5
595	30.2	498	29	340	26.3	300	24.5	479	28.2	426	27.5	156	17.8	350	26.6	486	28.5
540	29.2	420	28.1	354	26	234	22.4	689	31.6	286	22.4	154	20.2	240	22.3	540	29.2
570	24.2	260	24	182	21.6	244	22.8	349	26	300	25	147	18.2	246	22.5	660	32
790	32.2	330	25.4	302	25.3	280	22.2	680	31.6	140	16	131	15.3	230	22.4	432	28.4
600	28.1	363	27	230	22.8	150	19.4	502	29.1	422	27.4	281	22.1	321	25.6	503	29
430	28.3	256	23	219	22.6	244	22.3	509	29	328	26	182	21.1	181	21.2	680	32
426	27.5	245	22.6	160	20.3	291	24.6	453	28.2	348	24.6	170	16.4	148	17.6	637	30.3
		190	22	234	23.6	186	21.1			190	20.7	248	22.4	140	17.3		
		219	22.8	300	25.3	152	19.4			301	24	306	24.3	222	20.3		
		208	20.2	284	22.4	348	24.3			308	24.8	142	16.9	181	20.1		
		403	27.3	320	25.4	316	25.2			192	22.6	242	22.3	156	20.1		
		432	28.3	180	20.8	290	24.4			350	26.3	292	24.6	180	20.2		
		536	30.4	350	26.2	340	26.7			184	21	350	26.8	341	24.6		
		317	25.6	349	24.4	190	22.4			204	21	300	24.2	302	24.2		
		342	24.2	306	25.4	168	21.2			318	25.2	180	21.6	240	22.3		
		282	20.4	236	22.6	240	22.6			354	26.4	221	22.5	130	15.6		
		230	22.2	360	26.4	290	24.3			154	20.5	140	18.6	120	14.3		
		340	26.2	150	20.1	302	24.6			148	18	210	22.1	148	17.6		
		302	24.2	180	21.7	350	26.4			430	23.3	120	14.6	189	21.3		
		510	28.3	162	21	500	30.2			350	26.1	143	15.3	143	18.2		
		296	24.5	231	22.2	342	24.4			319	25.4	153	20.2	160	19.3		
		228	22.8	240	22.6	373	27			383	27	280	22.4	171	22.2		
		196	22.4	219	22.3	233	22.2			352	26.3	246	22.6	230	22.3		
		184	21.2	280	22.4	316	24.7			354	26	316	24.7	320	25.6		

480	28.5	140	18.2	354	26.2
144	18.1	180	21.2	368	27.4
160	19.3	318	24.4	245	22.6
350	26.4	182	21.3	182	20.8
432	28.3	230	22.6	230	22.8
182	21.4	340	26.4	220	22.9
510	29.8	150	19.3	188	21.2
430	28.4	300	25.1	160	21
208	20.1	308	25.4	254	22.6
278	20.4	221	22.3	300	25.6
470	27.6	162	20.6	342	26.8
		190	22.4	304	24.8
		301	24.6	318	25.4
		193	22.5	341	26.3
		180	21.7	337	25.7
		214	22.2	299	24.6
		338	25.5	336	22.8
		320	27.1	316	25.8
		308	25.6	230	23.2
		246	22.4	211	22.6
		180	21.2	220	22.6
		308	25.4	150	19.6
		281	22.6	304	24.3
		362	26.3	336	25.6
		363	27.6	361	26.6
		307	25.5	211	22.8
		270	22	290	24.4
				236	24.8

284	22.2	178	20.8	306	24.4
486	28.5	240	22.2	340	24.3
202	18.8	152	19.3	420	28.3
436	27.8	138	18.4	230	24.6
572	29.4	230	22.4	300	25.2
473	27.4	232	22.6	186	21.3
452	28.1	211	22.1	292	24.3
363	24.6	358	26.6	286	22.2
402	27	173	22.1	319	24.6
341	24.5	301	25.1	147	18.2
425	27.4	148	18.1	130	15.2
		183	21.3	150	17.4
		221	22.5	246	22.3
		243	22.3	180	21.3
		315	24.2	220	22.4
		209	22.6	160	21.2
		230	22.9	350	26.4
		219	22.5	173	22.1
		300	25.6	248	22.6
		280	22.4	321	25.6
		420	28.6	209	22.6
		342	26.7	240	22.3
		280	22.2	320	25.6
		318	24.7	280	23.2
		220	22.4	180	21.6
		248	22.5	130	15.3
		307	24.4	341	24.3
				318	25.4

301	24.4	341	26.3
184	21.4	337	25.7
430	28.3	299	24.6
222	22.9	336	22.8
231	22.8	316	25.8
146	18.8	230	23.2
304	22.2	211	22.6
209	22.9	220	22.6
340	25.3	150	19.6
280	22.2	304	24.3
341	26.4	336	25.6
152	19.6	361	26.6

Appendix IV: Similarity Report

University of Eldoret

Certificate of Plagiarism Check for Synopsis

Author Name	SELLU MAWUNDU SNAT/FAS/P/06/19
Course of Study	Type here...
Name of Guide	Type here...
Department	Type here...
Acceptable Maximum Limit	Type here...
Submitted By	titustoo@uoeld.ac.ke
Paper Title	ECOLOGICAL CARRYING CAPACITY AND GROWTH PERFORMANCE OF NILE TILAPIA (OREOCHROMIS NILOTICUS) IN CAGE AQUACULTURE WITHIN LAKE VICTORIA, KENYA
Similarity	11%
Paper ID	975821
Submission Date	2023-09-19 13:41:06

Signature of Student

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Head of the Department

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