EVALUATION OF MICROPLASTICS AND SELECTED HEAVY METAL CONTAMINANTS IN WATER AND SELECTED FISH SPECIES FROM LAKE VICTORIA, UGANDA

BY

GODFREY KATUMBA

21/U/GMCH/14223/PE

A DISSERTATION SUBMITTED TO THE DIRECTORATE OF RESEARCH AND GRADUATE TRAINING IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN CHEMISTRY OF KYAMBOGO UNIVERSITY

May, 2024

DECLARATION

I **Godfrey Katumba**, hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by any other person nor material which has been submitted for the award of any other degree of any university or institution of higher learning, except where due acknowledgement has been made in the text and reference list.

Signed: ……………………………… Date: …………………………………

APPROVAL

This research and the dissertation have been done under the supervision and guidance of the undersigned supervisors. They have approved it for submission to the Directorate of Research and Graduate Training of Kyambogo University for examination in partial fulfilment of the requirements for the award of the Degree of Master of Science in Chemistry of Kyambogo University.

Signature……………………………… Date……………………………………

Dr Christine Kyarimpa

Supervisor

Signature……………………………… Date…………………………………

Dr Grace Kizito Bakyayita

Supervisor

DEDICATION

I bestow these studies to my beautiful wife, Ritah, my beloved brother, Emmanuel, who have always inspired and supported me in all my endeavours. I couldn't have done it without you. I also dedicate this work to my children, Benjamin and Christal. You give me reasons to work harder.

ACKNOWLEDGEMENT

I express my heartfelt thanks to those who extended a hand in the development of these post graduate studies.

First and foremost, I appreciate Dr Christine Kyarimpa for her valuable feedback and guidance throughout the research process. Her insight and expertise were invaluable in shaping the research and its quality. Also, without the funding she provided, this research would be impossible.

I also give my appreciation to Dr Grace Kizito Bakyayita for his unreserved contribution to the whole research process. His knowledge, expertise, and dedication have been crucial in making this research a success.

I convey my appreciation to Dr Philip Kodi for his tremendous contribution in refining this research dissertation.

I acknowledge the support of Kyambogo University in providing the resources and support that enabled me to undertake this project. Their ongoing commitment to promoting graduate research is truly inspiring.

Finally, I appreciate all those who provided feedback and suggestions during the review process. Your input was invaluable in helping to refine and improve this research report.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS AND ACRONYMS

PE:	Polyethylene
ANOVA:	Analysis of Variance
HMs:	Heavy Metals
HDPE:	High Density Polyethylene
PVC:	Poly Vinyl Chloride
PET:	Polyethylene Terephthalate
MPs:	Microplastics
HMs:	Heavy Metals
NEMA:	National Environmental Management Authority
NWSC:	National Water and Sewerage Corporation
$ADID_i$:	Average Daily Intake Dose through ingestion
$ADID_d$:	Average Daily Intake Dose through dermal
WIR:	Water Ingestion Rate
EF:	Exposure Frequency
ED:	Exposure Duration
ABW:	Average Body Weight
AET:	Average Exposure Time
ESA:	Exposed Surface Area
DAF:	Dermal Absorption Factor
SAF:	Skin Adherence Factor

FIR:	Fish Ingestion Rate
CF:	Conversion Factor for fish
THQ:	Target Hazard Quotient
TCR:	Total Cancer Risk
ORD:	Oral Reference Dose
DRD:	Dermal Reference Dose
CHR_i:	Carcinogenic Health Risk due to ingestion
CSF:	Cancer Slope Factor
EDI:	Estimated Daily Intake
CREDI:	Cumulative Risk Estimation Daily Intake
BMF:	Biomagnification Factor
TMF:	Trophic magnification Factor
BCF:	Bioconcentration Factor
AAS:	Atomic Absorption Spectrophotometer
ATR-FTIR:	Attenuated Total Reflectance-Fourier Transform Infrared
CR:	Cancer Risk
DGAL:	Department of Government Analytical Laboratories

ABSTRACT

This study evaluated the presence, source and characteristics of MPs and HMs (Lead, Cadmium, Chromium, and Copper) in water and their bioaccumulation status in three commercial fish species of *C. gariepinus*, *L. niloticus,* and *O. niloticus* and from three landing sites of Wairaka, Katosi, and Portbell on the shores of Lake Victoria, Uganda. Human health risks from exposure to microplastics and heavy metal contaminants in water and fish were assessed. Conductivity, temperature, pH, and total dissolved solids in water samples were recorded using a portable pH/Temp/Cond/TDS meter. Fish length was measured with a tape measure, and wet weights were recorded using an analytical balance. Microscopic analysis of MPs was done using a stereospecific microscope. MP identity verification was done using an ATR-FTIR Spectrometer whereas HM analysis was done using an AAS. In water, Pb had the highest concentration observed at Wairaka site (1.46±0.11 ppm). Within the fish varieties, *O. niloticus* had the highest concentration of copper (0.31±0.36 ppm) at the Katosi site. MP abundance and types varied, with fibres, films, and microbeads being the predominant morphotypes which were mainly HDPE, PE or PVC type. In water, the highest number of microplastics was in Wairaka, followed by Portbell and Katosi with 30±0.63, 20±0.32, and 14±0.41 particles per litre respectively. In fish, O. niloticus had the highest microplastic concentrations in all the three species (24±1.36 particles per kg). The overall target hazard quotient values were less than 1, which suggests that there is no significant health risk linked with the intake of heavy metals through consuming water and fish or through direct skin contact. Total CR results were above 1×10^{-6} but below 1×10^{-4}. There is no evidence to suggest that consuming water and fish or coming into contact with water containing the specified heavy metal pollutants poses any risk of getting cancer

CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND OF THE STUDY

1.1.1 Lake Victoria

Lake Victoria in East Africa, is the biggest body of freshwater on the African continent, and second to Lake Superior globally. It spans an area of over 68,800 square kilometres (Benn *et al*., 2011). This iconic lake is not only a geographical landmark but also holds immense ecological and socio-economic significance. Lake Victoria is acknowledged as the principal origin of the White Nile, which is one of the two principal tributaries of River Nile. Its waters flow northward, merging with the Blue Nile in Sudan to form River Nile. The ecosystem of Lake Victoria supports a diverse array of fauna and flora, including many endemic species of fish, plants, and invertebrates. Moreover, it sustains a significant human population dependent on its resources. Over 30 million people inhabit the Lake Victoria basin, spanning several countries, including Uganda, Kenya, Tanzania, and parts of Rwanda and Burundi (Victoria *et al*., 2001). The fisheries industry in this region is a cornerstone of the economy, providing livelihoods for millions of people engaged in fishing, fish processing, and related activities. Conversely, Lake Victoria plays a crucial role in providing freshwater for domestic use, irrigation, transportation, and the production of hydropower in the neighbouring area. Despite its ecological importance and socio-economic contributions, Lake Victoria is burdened by natural and anthropogenic contamination and pollution from a variety of substances including silt, organics, plastics, wastes, inorganics, and nutrients. In the past two decades, various pollutants such as current-use pesticides, personal care products, poly-fluoroalkyl and per-fluoroalkyl compounds, heavy metals, cyanotoxins, and microplastics have been explored in fish, water column, and the sedimentary phase of Lake Victoria (Biginagwa *et al*., 2016; Egessa *et al*., 2020). While there has been several studies conducted and documented on contamination and pollution, there is a scarcity of research on the bioaccumulation and trophic transmission of microplastics, as well as their correlation with heavy metals in fish

1.1.2 Microplastics

Plastics, integral to numerous aspects of modern life, confer undeniable societal benefits. However, with the escalating production of plastic, an escalating challenge arises in waste management. Microplastics, are particles that have a size range of ranging from 100 nanometres to 5 millimetres (Thompson *et al*., 2016), emerge as a particularly menacing facet of plastic waste.

1.1.2.1 Sources of microplastics

Microplastics can be categorised into main and secondary. Main microplastics are directly introduced into the environment, without being the result of the breakdown of bigger plastic materials. Manufactured for a wide range of uses, such as microbeads in resin particles and face cleansers. Secondary microplastics are generated through environmental processes such as ageing, biodegradation, and weathering which cause larger plastic items to break down into smaller fragments(Green *et al*., 2017). Diverse sources: Stem from plastic waste, industrial processes, and microbeads in personal care products (Eriksen *et al*., 2014).

1.1.2.2 Transport of microplastics

Microplastics have been found in various aquatic environments across the world like in oceans, lakes, rivers, and tap water. Their widespread presence is attributed to the disintegration of larger plastic particles, improper waste disposal, and urban runoff. In marine environments, microplastics have been found from the surface water to the deepest parts of the ocean. In freshwater systems, rivers act as conduits transporting microplastics from land to sea, while lakes serve as reservoirs where microplastics accumulate (Galloway *et al*., 2017). Microplastics introduced into the food chain serve as vectors for organic pollutants, microbes, and other contaminants, significantly enhancing the exposure of aquatic organisms and humans to these harmful substances. These tiny particles can absorb and concentrate noxious chemicals like heavy metals and pesticides from water. When taken up by aquatic organisms, microplastics can transfer the toxins up the food chain, from smaller organisms like zooplankton to larger predators, including fish, shellfish, and marine mammals. This bioaccumulation and biomagnification process means that higher trophic level species, including humans who consume seafood, are at risk of ingesting higher concentrations of these harmful chemicals (Ahmed *et al*., 2022).

1.1.2.3 Fate of the microplastics

According to (Wright *et al*., 2013), microplastics can bioaccumulate in the tissues of aquatic organisms, meaning that these tiny particles can be consumed and retained in the bodies of the organisms over time. This process begins at the lower levels of the food chain, where tiny organisms like plankton inadvertently consume microplastics. As these tiny organisms are eaten by larger predators, the microplastics are transferred up the food chain, leading to elevated concentrations in upper trophic level organisms such as fish, shellfish, and even marine mammals. The endurance of microplastics in the environment worsens this issue, as they do not readily degrade. They can remain in various water bodies including rivers, oceans, lakes, and tap water, posing long-term environmental challenges. In aquatic environments, microplastics were found in sediments, on the surface, and within the water column. This widespread distribution indicates that microplastics can impact a wide range of marine organisms and habitats.

Moreover, presence of microplastics disrupts ecosystems by introducing physical and chemical stressors. Physically, the ingestion of microplastics leads to internal blockages, reduced nutrient absorption, and damage of digestive organs in marine organisms. Chemically, microplastics can absorb and transport heavy metals which can leach out and cause toxic effects in organisms that ingest them. The bioaccumulation of MPs and associated contaminants poses significant risks to individual species and the health of entire ecosystems. Predatory species that rely on contaminated prey may suffer from impaired growth, increased mortality rates, and reduced reproductive success. These ecological impacts can lead to shifts in species populations and community structures, consequently affecting the biodiversity and functioning of aquatic ecosystems (Miller *et al*., 2020)

1.1.2.4 Exposure to microplastics

Humans are exposed through the ingestion of seafood contaminated with microplastics, contaminated food, water, beverages, or inhalation of particles in air (Van Cauwenberghe & Janssen, 2014). Microplastics can leach from food packaging materials into food and beverages, contributing to human exposure (Yang *et al*., 2020).

1.1.2.5 Intake of microplastics

Microplastics have been detected in seafoods like crustaceans, fish, and shellfish (Van Cauwenberghe & Janssen, 2014) and can migrate from packaging materials during food processing, storage, and transportation (Yang *et al*., 2020)

1.1.2.6 Health risks of microplastics

Microplastics pose potential adverse health effects such as inflammation, oxidative stress, and accumulation of toxic chemicals associated with them (Lu *et al*., 2022). They impair the health and reproductive success of aquatic organisms, leading to potential toxic effects on the health of humans through ingestion of contaminated seafood (Wright *et al*., 2013; Galloway *et al*., 2017)

Microplastics are a significant environmental concern globally, with an estimated 11 million tonnes of waste finding their way into oceans annually, much of which degrades into microplastics (UNEP, 2021). These particles have been spotted in human lungs, blood, breast milk, and placentas raising serious apprehensions about their long term effects on health (Leslie *et al*., 2022; Ragusa *et al*., 2021). Scholars suggest that an average person may ingest up to 5 grams of microplastics weekly (WWF, 2019). Additionally, plastic pollution affects over 800 marine species through ingestion or entanglement (IUCN, 2021).

In Africa, microplastics are increasingly detected in major water bodies like Lakes Victoria and Tanganyika and River Nile (Biginagwa *et al*., 2016; Nel *et al*., 2017). Inadequate waste management in urban centers leads to high plastic leakage into the environment; for instance, Kampala generates over 750 tonnes of plastic waste daily, much of which ends up in drainage systems and water bodies (NEMA Uganda, 2020). This threatens human health and ecosystems, especially in fishing communities that depend on clean water for their existence (UNEP Africa, 2020).

In Uganda, microplastic pollution is most evident in Lake Victoria, where research by Makerere University found microplastics in fish and drinking water sources, with up to 70% of sampled fish containing plastic particles (Nabwire *et al*., 2021). Furthermore, microplastics have been found in soils near urban areas like Kampala and Jinja, potentially impacting agricultural productivity (Mwesigye *et al*., 2022). While Uganda implemented a ban on plastic bags thinner than 30 microns in 2007, enforcement has been weak and inconsistent (NEMA, 2020). Nonetheless, universities, NGOs, and environmentalists continue to advocate for better policies and public awareness.

1.1.3 Heavy metals

Heavy metals (HMs) are metals with high density (3.5 to 9.0 gcm^{-3}) and likely to cause harmful effects on living organisms. They are are categorized into essential and non essential heavy metals. Essential heavy metals, like iron (Fe), zinc (Zn), copper (Cu), cobalt (Co), and manganese (Mn), are integral to various biological processes and are required in trace quantities for optimal health (Chen *et al*., 2009). These metals serve as cofactors for enzymes in essential functions like energy production, oxygen transport, and antioxidant defense mechanisms. While essential for life, excessive intake of these metals can lead to toxicity, necessitating regulated intake through dietary sources and supplements (Chen *et al*., 2009). Deficiencies in essential heavy metals can result in impaired growth, weakened immune function, and other health problems, highlighting their critical role in maintaining physiological balance. In comparison, non essential heavy metals like mercury (Hg), lead (Pb), cadmium (Cd), and arsenic (As) have no known biological function and present notable health risks even at low concentrations (Ma *et al*., 2013). Introduced into the environment primarily through mining, industrial discharges, and improper waste disposal, these metals can accumulate in tissues and interfere with biological processes, leading to organ damage, neurological disorders, and cancer. Due to their toxicity, non essential heavy metals are subject to strict regulatory limits in environmental and occupational settings to protect the environment and the human health, emphasizing the importance of understanding and mitigating their adverse effects.

1.1.3.1 Copper (Cu)

Copper, a transition metal with an atomic number of 29, belongs to Group 11 of the periodic table with a density of 8.99 g/cm^3. It is naturally present in the environment, with primary sources including natural mineral deposits, mining activities, and various industrial operations. Use of fertilizers and pesticides containing copper and improper disposal of wastes also adds up to environmental copper levels (Chen *et al*., 2009). Copper is widely used in electrical wiring, plumbing, coinage, and in alloys such as brass and bronze. It is also used in electronics, roofing materials, and as a biocide in agriculture (Akram *et al*., 2015). Copper is naturally occurring and can be transported through water runoff, industrial effluents, and atmospheric deposition. Commonly found in water, air, and soil (Ali *et al*., 2019). Human beings can be exposed to copper via intake of contaminated water and food, particularly in areas with high industrial activity. Occupational exposure can occur in industries dealing with copper processing (Akram *et al*., 2015). Copper is a vital component of many enzymes, including cytochrome c oxidase, which is essential for cellular respiration. It is also involved in iron metabolism, antioxidant defense, and the synthesis of connective tissue and neurotransmitters (Shafiuddin Ahmed *et al*., 2019). While essential in trace amounts, excessive copper intake can lead to toxicity. Acute exposure can cause gastrointestinal distress, while chronic exposure may result in kidney and liver damage, and neurological issues such as mood swings and cognitive impairment (Ma *et al*., 2013; Lu *et al*., 2022).

1.1.3.2 Lead (Pb)

Lead has an atomic number of 82, belongs to Group 14 of the periodic table with a density of approximately 11.34 g/cm³. Lead contamination comes from various sources, including natural mineral deposits, industrial activities including smelting, mining, and fossil fuel combustion (Chen *et al.*, 2009). Additionally, lead-based paints, batteries, and plumbing materials contribute significantly to environmental lead levels. Improper waste disposal exacerbates contamination, posing risks to both human and environmental health (Akram *et al.*, 2015). Lead finds application in numerous industries due to its malleability, resistance to corrosion, and low melting point. Historically used in plumbing, lead pipes and solder are still present in older buildings, potentially contaminating drinking water. Lead-acid batteries, ammunition, and radiation shielding represent additional uses. Lead is transported through air, water, and soil, primarily via atmospheric deposition and water runoff. Once released, lead can stay in the environment for longer periods, accumulating in soil and sediment. Human exposure occurs via ingestion, inhalation, and dermal contact, posting notable risks to health (Ali *et al.*, 2019). Exposure to lead presents considerable health risks for vulnerable populations like children and pregnant women. Lead toxicity can result in developmental delays, neurological damage, impaired cognitive function, cardiovascular issues, kidney damage, and reproductive problem (Ma *et al.*, 2013).

1.1.3.3 Cadmium (Cd)

Cadmium, a metal with an atomic number of 48, belongs to Group 12 of the periodic table with a density of approximately 8.65 g/cm³. Cadmium contamination arises from various sources, including natural mineral deposits, mining, smelting, and the production of products that contain cadmium. Additionally, cadmium is brought into the environment through fossil fuel combustion, waste incineration, and the use of phosphate containing fertilizers. Improper disposal of cadmium-containing products further contributes to environmental contamination, presenting risks to both ecosystems and human health (Chen *et al*., 2009). Cadmium has several industrial applications due to its corrosion resistance and ability to conduct electricity. It is commonly used in batteries, pigments, electroplating, and as a stabilizer in plastics. Cadmium is utilized in the production of solar cells, semiconductors, and nuclear reactors (Akram *et al*., 2015). Cadmium can be transported through air, water, and soil, primarily via atmospheric deposition, water runoff, and leaching from contaminated soil. Once released, cadmium can last in the environment for prolonged periods, amassing in soil, sediments, and aquatic organisms. Human exposure occurs via ingestion of water and food that are polluted, dermal contact, and inhalation of airborne particles, posting material risks to health (Ali *et al*., 2019). Exposure to cadmium presents notable health risks to individuals with low immune systems like the children and pregnant women. Cadmium toxicity can result into serious health effects like kidney damage, respiratory problems, bone demineralization, cardiovascular issues, and cancer (Afzaal *et al*., 2022).

1.1.3.4 Chromium (Cr)

Chromium, a transition metal with an atomic number of 24, belongs to group VI of the periodic table with a density approximating 7.19 g/cm^3. Chromium contamination stems from various sources, including natural mineral deposits, mining, smelting, and the production of products that contain chromium. Chromium is also let out into the environment through activities such as metal plating, leather tanning, and the use of chromium-containing dyes and pigments. Improper disposal of waste containing chromium further contributes to environmental contamination, posting risks to human and ecosystems health (Afzaal *et al*., 2022). Chromium has diverse industrial applications due to its corrosion resistance, hardness, and ability to withstand high temperatures. Chromium is commonly used in production of stainless steel, metal plating, and in manufacture of alloys such as nichrome. Moreover, chromium compounds are utilized in leather tanning, textile manufacturing, and the production of paints, ceramics, and refractory materials (Chen *et al*., 2009). Chromium can be transported through air, water, and soil, primarily via atmospheric deposition, water runoff, and leaching from contaminated soil. Once released, chromium can stay in the environment for prolonged periods, aggregating in soil, sediment, and aquatic organisms. Human exposure occurs through breathing in of particles from air, ingestion of polluted water and food, and dermal contact, presents notable risks to health (Ali *et al*., 2019). Exposure to chromium presents notable health risks for vulnerable populations like workers in chromium-related industries and individuals living in contaminated areas. Chromium toxicity can result into adverse health effects like skin irritation, respiratory problems, kidney damage, liver dysfunction, and cancer (Ma *et al*., 2013).

1.2 STATEMENT OF THE PROBLEM

While previous investigations studied the presence of heavy metal contaminants and microplastics in fish and water from Lake Victoria, a critical knowledge gap exists regarding bioconcentration as well as their implications for ecosystem health and human well-being. Microplastics, due to their persistence and capability to adsorb and carry other pollutants, present a particular concern as they can amass in aquatic organisms, potentially causing physical harm, internal injuries, and gastrointestinal blockages in fish, while also serving as vectors, transferring associated contaminants, including HMs, through the food web. Likewise, HMs, known for their toxicity and persistence in aquatic environments, can amass in fish tissues, posting risks to both aquatic organisms and humans consuming contaminated fish. Prolonged exposure to high levels of HMs such as lead and cadmium can lead to detrimental health effects in humans like neurological disorders, developmental abnormalities, and cardiovascular diseases. Despite recognizing potential risks, comprehensive data on contamination levels, distribution patterns, and associated impacts are lacking. This study intended to resolve this gap by evaluating levels of MPs and selected HMs in targeted fish species and water, identifying sources and distribution patterns, investigating bioconcentration dynamics, and determining potential health risks.

Therefore, conducting a comprehensive evaluation of microplastics and selected HM contaminants in water and targeted fish species from Lake Victoria is crucial to weigh the extent of contamination and potential risks to the ecosystem and human health.

1.3 JUSTIFICATION OF THE STUDY

Lake Victoria is under intense anthropogenic pressure and considered to be a major sink for pollutants from the three riparian countries of Uganda, Kenya, and Tanzania. However, few studies have examined the concentrations, apportioned sources, and investigated any possible trophic transfer and bioaccumulation of MPs and HM contaminants in its fish resources. Furthermore, studies in this lake have not examined the relationship between HM contaminants and MPs concentration, and human health risks from direct dermal contact with and ingestion of water and fish that is with heavy metals. Therefore, the study generated scientific data which would be used to strengthen MPs and HMs pollution mitigation interventions in L. Victoria that can be used to inform policy specifically NEMA, Ministry of Water and Environment and the National Water and Sewerage Corporation.

1.4 OBJECTIVES OF THE STUDY

1.4.1 General Objective

To investigate the levels, bioaccumulation, and trophic transfer, and potential human carcinogenic health risks linked with MPs and selected HM contaminants in targeted fish species and water from L. Victoria, Uganda.

1.4.2 Specific Objectives

(1) Determine the levels of MPs in targeted fish species and water from L. Victoria, Uganda.

(2) Ascertain the levels of selected HM contaminants in targeted fish species and water from L. Victoria, Uganda.

(3) Analyse the bioaccumulation of MPs and selected HM contaminants in targeted fish species from L. Victoria, Uganda.

(4) Figure out the potential human carcinogenic health risks linked with the dermal contact and ingestion of fish and water contaminated with MPs and the selected HM contaminants from L. Victoria, Uganda.

1.5 RESEARCH HYPOTHESES

1) Microplastic levels in Lake Victoria's water and fish vary based on geography and anthropogenic activities.
2) Heavy metal contaminants in Lake Victoria's water and fish have variable levels and sources influenced by natural processes and anthropogenic activities.
3) Microplastic pollution and heavy metal contamination in Lake Victoria show a positive correlation, suggesting an interaction between these pollutants.
4) Heavy metals bioaccumulate in targeted fish from Lake Victoria, leading to trophic transfer and potential risks for fish and human consumers.

1.6 SIGNIFICANCE OF THE STUDY

The study has notable implications for environmental conservation, public health, fisheries management, policymaking, and scientific research. By evaluating microplastics and heavy metal contamination levels in Lake Victoria's water and fish species, it provides crucial insights into the lake's ecosystem health, guiding conservation efforts and public health initiatives. Furthermore, it informs fisheries management practices, supports policymaking for pollution reduction and sustainable resource management, and contributes valuable data to scientific research on freshwater ecosystems and human health impacts. Overall, this study's findings drive evidence-based decision-making to protect Lake Victoria's ecosystem and the well-being of communities reliant on its resources.

1.7 SCOPE OF THE STUDY

1.7.1 Geographical Scope

The study area was Northern Lake Victoria in East Africa, bordering three countries, namely Tanzania, Uganda, and Kenya. The lake covers a surface area of approximately 59,000 km^2, making it the largest lake in Africa and the second in the world (Biginagwa *et al*., 2016). The northern part of Lake Victoria is primarily influenced by the inflow of rivers, including the Nile and its tributaries. The area is densely populated, with numerous small towns and fishing villages along the lake's shore. The lake is such an important source of livelihood for a lot of people in the region, with fishing being a major economic activity. However, the lake has been facing numerous environmental challenges, including pollution from various sources, overfishing, and invasive species. The study focused on three landing sites in Uganda, which included Wairaka, Katosi and Portbell fish landing sites which are in Jinja, Mukono and Kampala districts, respectively. Wairaka is located at 0° 42' 2" N, 33° 13' 30" E, Katosi is located at 0° 10' 31" N, 32° 22' 30" E, while Portbell is located at 0° 10' 31" N, 32° 22' 30" (**Figure 1**). These sites were chosen because they are located in Urban, rural, and industrial districts of Uganda respectively. Furthermore, the sites were selected because they had never been assessed for microplastic pollution before (Egessa *et al*., 2020).

Figure 1: Location of Wairaka, Katosi, and Portbell in Uganda

1.7.2 Content Scope

For Microplastics, the type, shape, size, and quantity of items present in the water and fish samples of Clarias gariepinus, Oreochromis niloticus and Lates niloticus, their chemical composition, and how they are distributed within the samples were determined.

For HMs, the concentration of Cr, Cu, Cd, and Pb in the sample, their distribution and potential sources were determined.

1.7.3 Time Scope

The study was conducted from October 2022 to June, 2024, that included laboratory work, writing and data analysis, submission of the dissertation, and defense.

1.8 LIMITATIONS AND DELIMITATIONS

1.8.1 Limitations

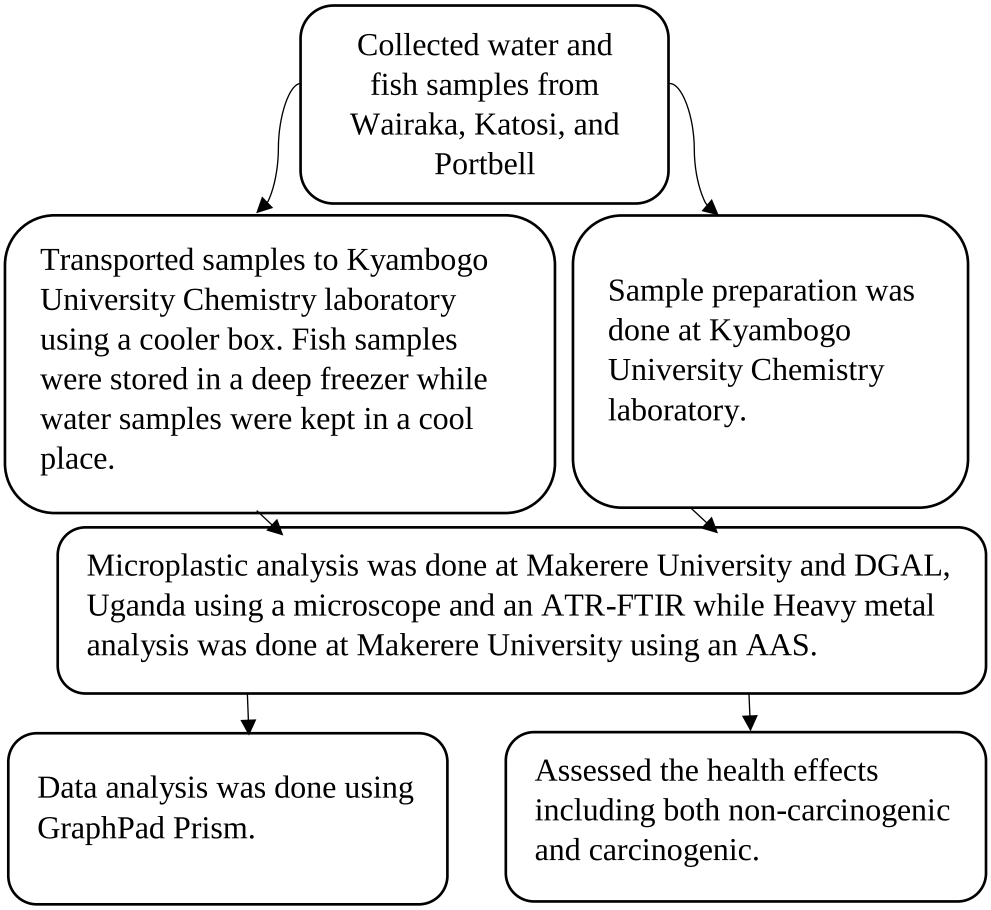
During this research, the shortcomings included;

Biases in sampling methods, Limitations in the detection sensitivity of analytical techniques, Challenges in assessing long-term exposure effects, Complexity of interactions within the ecosystem.

1.8.2 Delimitations

The above limitations were mitigated as follows: Biases in sampling methods was mitigated by limiting the study to specific regions or sampling sites within Lake Victoria due to logistical constraints or the focus on areas with known pollution hotspots. Limitations in the detection sensitivity of analytical techniques was achieved by restricting the analysis to certain analytical methods or detection limits based on available resources and expertise. Challenges in assessing long-term exposure effects were handled by narrowing the study to a specific time period to capture seasonal variations or historical trends in contamination levels, acknowledging that longer-term trends may not be fully captured. Complexity of interactions within the ecosystem was reduced by focusing on specific fish species to provide depth to the analysis, recognizing that other species or components of the ecosystem may be affected but are not included in this study.

1.9 CONCEPTUAL FRAMEWORK



Collected water and fish samples from Wairaka, Katosi, and Portbell

Transported samples to Kyambogo University Chemistry laboratory using a cooler box. Fish samples were stored in a deep freezer while water samples were kept in a cool place.

Sample preparation was done at Kyambogo University Chemistry laboratory.

Microplastic analysis was done at Makerere University and DGAL, Uganda using a microscope and an ATR-FTIR while Heavy metal analysis was done at Makerere University using an AAS.

Data analysis was done using GraphPad Prism.

Assessed the health effects including both non-carcinogenic and carcinogenic.

CHAPTER TWO: LITERATURE REVIEW

2.1 MICROPLASTICS IN FISH AND WATER

In recent years, the global sustainability agenda has increasingly recognized the significance of rapid economic growth, industrialization, and urbanization as markers of development. However, these indicators often come at a significant cost to the environment. Inadequate regulatory structures, particularly in developing countries, exacerbate the challenges posed by environmental pollution (Mitra *et al*., 2022). Among the most tenacious concerns is the contamination of water resources with various contaminants, which posts a severe threat to water security and hampers the achievement of sustainable development goals. Microplastics range from 100 nm to 5 mm in size (Rampley *et al*., 2020). They have emerged as a perilous issue in environmental science. These minuscule plastic particles can originate from breakdown of larger plastic items, industrial processes, and microbeads in personal care products (Cole *et al*., 2011). There exist two categories of microplastics, primary and secondary. Primary microplastics, produced extensively for diverse applications like microbeads in resin particles and facial cleansers, pose distinct environmental concerns (Bayo *et al*., 2020). Conversely, secondary microplastics result from the spitting of larger plastic items through aging, biodegradation, and weathering (Gouin *et al*., 2011). The microplastics likely originate from different sources, including household waste, industrial activities, and other anthropogenic actions. Once introduced into the food chain, microplastics become vectors of organic pollutants, microbes, and other contaminants, significantly enhancing the exposure of aquatic organisms and humans to these harmful substances (Ahmed *et al*., 2022). The microplastics stem from numerous sources like plastic waste, industrial processes, and microbeads used in personal care products (Eriksen *et al*., 2014). Microplastics have been found in numerous water bodies worldwide, including oceans, rivers, lakes, and even tap water (Galloway *et al*., 2017). Numerous studies have demonstrated the ingestion of microplastics by aquatic organisms at different trophic levels, including zooplankton, fish, shellfish, and even larger aquatic mammals (Cole *et al*., 2011). Microplastics can bioaccumulate in aquatic organisms, leading to higher concentrations as they move up the food chain (Wright *et al*., 2013). This bioaccumulation presents risks to predators, including humans, who eat seafood contaminated with microplastics (Rochman *et al*., 2013). Research has shown that the ingestion of microplastics can have adverse effects on marine organisms, including impaired feeding, reproductive issues, and internal injuries. These effects can disrupt ecosystems and affect the health of commercially important fish species (Wright *et al*., 2013). Human beings can be exposed to microplastics via ingestion of seafood contaminated with these particles (Van Cauwenberghe & Janssen, 2014). Studies have detected microplastics in different seafood products, including fish, shellfish, and crustacean. Apart from seafood consumption, human beings can also be exposed to microplastics via inhalation of airborne particles or ingestion of contaminated food, water, or beverages (Schwabl *et al*., 2019). Microplastics can leach from food packaging materials into food and beverages, contributing to human exposure (Yang *et al*., 2021.). This exposure route is particularly concerning as microplastics can migrate from packaging materials during food processing, storage, and transportation. While the health impacts of microplastic exposure in human beings are being studied, there are concerns about potential adverse effects, including oxidative stress, inflammation, and the accumulation of toxic chemicals associated with microplastics (Wagner & Lambert, 2018). Microplastic contamination in aquatic ecosystems can have harmful effects on biodiversity, impairing the health and reproductive success of aquatic organisms (Wright *et al*., 2013). Additionally, microplastics can accumulate in fish and other aquatic organisms, leading to potential toxic effects on human health through the ingestion of contaminated seafood (Galloway *et al*., 2017). Research anticipates that exposure to high levels of microplastics, either through direct contact or consumption of contaminated water or seafood, can lead to a range of health concerns in humans. While the full extent of these concerns is being studied, research suggests potential links to oxidative stress, inflammation, and interruption of the gut microbiome, with implications for overall health and well-being (Lu *et al*., 2022).

2.2 HEAVY METALS IN FISH AND WATER

Heavy metals, including cadmium, lead, chromium, copper among others, are another group of pervasive water contaminants (Khan *et al*., 2019). They occur naturally and are often used in various materials, appliances, and industrial processes. These elements are characterized by their high densities, typically five times that of water (Akram *et al*., 2015), and they can be noxious when their concentrations surpass established threshold limits. The sources of HMs in fish and water include industrial discharges, agricultural runoff, urban runoff, mining activities, waste disposal, bioaccumulation from water, food chain transfer, and sediment contamination (Tchounwou *et al*., 2012). Heavy metals are classified into essential and non essential categories.

2.2.1 Essential heavy metals

Essential heavy metals are those that play crucial roles in biological processes and are obligatory for the survival of living organisms in minute quantities. They include: Iron (Fe) which is a component of myoglobin and hemoglobin and vital for oxygen transport and cellular respiration. Iron is also critical for various enzymatic processes (Krewski *et al*., 2007). Zinc (Zn) is vital for numerous enzymatic functions, protein synthesis, and immune system operation. It plays a role in DNA synthesis and cell division (Prasad, 2013). Copper

(Cu) is important for iron metabolism, connective tissue formation, and proper functioning of the nervous system. Copper is a component of several enzymes (Gaetke & Chow, 2003). Manganese (Mn) is necessary for bone formation, blood clotting, and the regulation of blood sugar. Manganese acts as a cofactor for many enzymes (Aschner & Aschner, 2005). Cobalt (Co) is an integral part of vitamin B12, which is vital for the production of erythrocytes and the maintenance of the nervous system (Hu *et al*., 2021). Chromium (Cr) enhances insulin action and is involved in the metabolism of fats, proteins, and carbohydrates (Vincent, 2010).

2.2.2 Non essential heavy metals

These heavy metals do not have known biological function and are often toxic even at low concentrations. Prominent non essential heavy metals include: Lead (Pb), known for its neurotoxicity, especially in children, developmental delays, cognitive deficits, and various health issues (Needleman, 2004). Mercury (Hg) is highly toxic, particularly in its methylmercury form. It affects the CNS and can cause neurological and behavioural disorders (Mutter *et al*., 2007). Cadmium (Cd) is toxic to the bones, kidneys, and respiratory system. Chronic exposure can lead to renal dysfunction, bone demineralization, and cancer (Järup, 2003). Arsenic (As) is carcinogenic and can cause skin lesions, cardiovascular diseases, and diabetes. Arsenic exposure is typically through contaminated water and food (Naujokas *et al*., 2013).

2.2.3 Deficiency of essential heavy metals

The deficiency of these essential heavy metals can lead to different health complications: Iron deficiency causes anaemia, characterized by fatigue, weakness, and impaired cognitive function. Severe deficiency can lead to developmental issues in children (McLean *et al*., 2009). Zinc deficiency results in growth retardation, hair loss, impaired immune function, diarrhea, and delayed wound healing (Prasad, 2013). Copper deficiency leads to anemia, neutropenia, bone abnormalities, and cardiovascular issues (Linder & Hazegh, 1996). Manganese deficiency is rare but can cause skeletal deformation, impaired growth, and reproductive issues (Aschner & Aschner, 2005). As part of vitamin B12, cobalt deficiency can lead to neurological disorders and pernicious anemia (Hu *et al*., 2021). Chromium deficiency can lead to impaired glucose tolerance, weight loss, and neuropathy (Vincent, 2010).

2.2.4 Effects of Non essential heavy metals

The effects of non essential heavy metals are predominantly toxic. Lead poisoning causes severe neurological impairment, especially in children, and can lead to chronic health problems like hypertension and renal dysfunction in adults (Needleman, 2004). Mercury toxicity manifests as Minamata disease, characterized by sensory disturbances, ataxia, and vision and hearing impairment, chronic exposure affects cognitive and motor functions (Mutter *et al*., 2007). Chronic exposure to cadmium results to kidney damage, bone fractures, and respiratory issues. It is also a human carcinogen (Järup, 2003). Long-term exposure tor arsenic leads to skin changes, cardiovascular disease, and increased risks of cancers of the skin, lungs, and bladder (Naujokas *et al*., 2013).

2.2.5 Health risks associated with heavy metals

Heavy metals present notable health risks due to their bioaccumulative nature and persistence in the environment. Once in the body, they can interfere with metabolic processes, causing toxic effects that range from acute symptoms to chronic diseases and cancer (Tchounwou *et al*., 2012). Some of these heavy metals can be bio-accumulative and toxic to living organisms at high concentrations or after chronic exposure to low concentrations (Ali *et al*., 2019).

Heavy metal contamination in aquatic ecosystems can have harmful effects on biodiversity, impairing the health and reproductive success of aquatic organisms (Sarkar *et al*., 2021). Exposure to elevated levels of heavy metals, either through direct contact or ingestion of contaminated water or seafood, can lead to a range of health problems in humans, including neurological disorders, organ damage, and cancer (Chen *et al*., 2009).

2.2.6 WHO allowable limits of heavy metals

The (WHO, 2011) highlights guideline values for heavy metals in drinking water to protect public health as 0.01, 0.006, 0.003, 0.01, 0.3, 3, 2, 0.4, and 0.05 mg/L for Lead, Mercury, Cadmium, Arsenic, Iron, Zinc, Copper, Manganese, and Chromium respectively.

2.2.7 The link between microplastics and heavy metals

According to (Miller *et al*., 2020), microplastics can adsorb and transport heavy metals from one place to another. Both human beings and aquatic organisms can be exposed to microplastics and heavy metals through different pathways. These routes include direct ingestion, dermal absorption, inhalation, and exposure through food, water, and medicine (Sarkar *et al*., 2021). Ingestion of heavy metal contaminants in contaminated drinking water and foods remains the most common route of exposure other than inhalation. Lake Victoria, the largest freshwater lake in Africa and a significant water source for Uganda, has been reported to have heavy metal contamination in both its water and fish (Fredrick, 2021). Microplastics have also been detected in various components of Lake Victoria, including surface water, fish, and sediments (Biginagwa *et al*., 2016; Egessa *et al*., 2020). The pollution of water and other matrices from Lake Victoria not only affects humans but also poses severe ecological challenges (Khalid *et al*., 2021). Microplastics, in their role as vectors for other pollutants, can amplify the ecological impact of heavy metals in aquatic systems (Liu *et al*., 2021). This intricate interaction between microplastics and heavy metals underscores the need for comprehensive research into their combined effects on the health of aquatic organisms and the environment (Alava, 2020). Ingestion of fish and water contaminated with heavy metals and microplastics can lead to various health issues, including gastrointestinal problems, stunted growth, neurological disorders, cardiovascular diseases, and even cancer (Ahmed *et al*., 2022). Wright *et al*., 2013 made a review on the physical impacts of microplastics on marine organisms and found out that microplastics can accumulate in various trophic levels, starting from primary producers like phytoplankton to zooplankton and eventually to larger fish. Heavy metals, on the other hand, can accumulate in fish tissues, including muscle, gills, and liver, depending on the metal's properties and the fish species (Qin *et al*., 2021) hence fish serve as vectors for these heavy metal contaminants.

CHAPTER THREE: MATERIALS AND METHODS

3.1 SAMPLING METHODS

3.1.1 Water sampling methods

Surface water was collected from each landing site using a manta trawl with the help of fishermen and boats (Egessa *et al.*, 2020). Surface water sampled instead of deep water or sediments due to its accessibility, relevance to aquatic life and human interaction, and its role as an indicator of overall water quality.

3.1.2 Fish sampling methods

The trawling method using baited nets was employed, with assistance from fishermen at each fish landing site, to sample *C. gariepinus, O. niloticus, and L. niloticus*. The choice of the fish species sampled over other species in Lake Victoria was due to their importance for local fisheries, their ecological significance, and their popularity as food sources among communities living around the lake (Kubečka *et al*., 2012).

3.1.3 Sample handling and transportation

The fish samples were wrapped in an aluminium foil while the water samples were kept in the plastic water bottles. Both the fish and water were transferred into an ice box and transported to Kyambogo University Chemistry laboratory, East end. The water samples were kept in a cool, dry place inside the laboratory while the fish were kept in a deep freezer up to the time of preparation.

3.2 SAMPLE SIZE

The sample size, n, was based on the equation below;

$$\mathrm{n} = \left(\frac{\mathrm{Z} \times \delta/2}{e} \right)^2$$

Where n = sample size, Z = Z-value, which corresponds to the chosen confidence level (Z = 1.96 for 95% confidence), σ = estimated standard deviation in the population, and e = desired error margin.

Each site was sampled three times in an interval of five days between sampling. Twenty seven water samples and twenty seven fish samples were collected. On each day, three surface water samples were collected from each landing site one metre from the shore (W1), thirty metres from the shore (W2) and sixty metres from the shore (W3). Each day, one Catfish (*Clarias gariepinus*) (C), one Nile tilapia (*Oreochromis niloticus*) (T) and one Nile perch (*Lates niloticus*) (P) representing different trophic levels were sampled from each fish landing site of Wairaka (W), Katosi (K) and Portbell (P).

3.3 LABORATORY SAMPLE PREPARATIONS

3.3.1 Sample preparations for evaluation of microplastics in water

The solid phase extraction method was used (Egessa *et al*., 2020). Here, each water sample (100 mL), hydrogen peroxide (20 mL, 30%), and acidified ferrous sulphate (20 mL, 0.05M) were mixed followed by sodium chloride (30 g) and stirred at 75 °C, transferred to a density separator and kept for 24 hours. The mixture was filtered on a Whatman glass microfibre filter (No. 1001125 125 mm) inside Pyrex glass funnels. The glass microfibre filters containing microplastics were then transferred into glass petri dishes, air-dried, and covered with an aluminium foil.

3.3.2 Sample preparations for evaluation of microplastics in fish

The Solid-liquid extraction method was used (Victoria & Nicholson, 2021). Here, the wet fish muscles were ground. Muscles (10 g) were mixed with potassium hydroxide (30 mL, 4 M), and hydrogen peroxide (5 mL, 30%). The mixture was stirred at 200 rpm and 75 ^{o}C using a magnetic heated stirrer (Model 78-1, China) for 1 minute and kept for 24 hours. The mixture was filtered on a Whatman glass microfibre filter inside Pyrex glass funnels. The glass microfibre filters containing microplastics were then transferred into glass petri dishes, air-dried, and covered with an aluminium foil. The glass microfibre filters were viewed under a stereoscopic microscope (Stemi 508) to determine their characteristics such as color (transparent, blue, black, red, and green among others) and morphotypes (filaments, films, fibre and microbead. Visual counting of the number of MPs per sample was performed. Plastic polymers from water and fish muscles were subjected to ATR-FTIR spectroscopy (IRTracer-100) between 4000 cm^{-1} and 650 cm^{-1}. The spectra were analyzed in reference to library standards. After, the common uses and potential sources of the MPs were predicted based on the polymer types.

3.3.3 Sample preparations for evaluation of heavy metals in water

Filtration and acid digestion methods were used (Dadebo & Gelaw, 2024). Here, each water sample (100 mL) was filtered through filter paper to remove suspended solids and mixed with concentrated nitric acid (2 mL). The acidified water samples were kept for 1 day and filtered on Whatman filter papers (No. 1001125 125 mm) inside Pyrex glass funnels. The solutions were transferred into clean sample bottles (Greiner bio-one falcon tubes) and sealed.

3.3.4 Sample preparations for evaluation of heavy metals in fish

Acid digestion and solid-liquid extraction methods were used (Kubečka *et al*., 2012). Fish muscles were dried at 105 ^{o}C for 3 hours in an oven (DHG-9023A, China) to constant weight. The muscles were ground into fine powder, and each sample (2 g) was ashed at 600°C for 6 hours in a muffle furnace (Model: FHP-03, Korea). The ashed samples were transferred into volumetric flasks (100 mL) and digested with aqua regia (15 mL) for 1 day. The samples were filtered into volumetric flasks (100 mL) on Whatman filter papers (No. 1001125 125 mm) inside Pyrex glass funnels and made to the mark with distilled water. The solutions were then transferred into clean sample bottles (Greiner bio-one falcon tubes) and sealed.

3.4 DETERMINATION OF WATER QUALITY PARAMETERS

Temperature, conductivity, pH, and Total Dissolved Solids of water samples were measured using a portable pH/Temp/Cond/TDS meter (Consort, C6010, S/N: 111657, Belgium).

3.5 DETERMINATION OF MICROPLASTICS IN THE SAMPLES

Microscopic analysis of microplastics was done at the Department of Chemistry, Makerere University. Each dry glass microfibre filter was viewed under a stereospecific microscope (Stemi 508) for any microplastic particles. The glass microfibre filter was put on the stage and the focus adjusted using the knob. Physical counting of the microplastic particles was done and photos taken. The glass microfibre filters that had the microplastic particles were taken to the Directorate of Government Analytical Laboratories, Uganda for microplastic identity using an ATR-FTIR Spectrometer (IRTracer-100). After the background measurement, the glass microfibre filter was put on the holder with a hole and the holder put on the stage of the system. The microplastics were first viewed with a white view camera and then with an IR microscope camera. The system analysed each particle and a spectrum obtained. The system compared each spectrum with the data base to identify the microplastic (Schymanski *et al*., 2021).

3.6 DETERMINATION OF HEAVY METALS IN THE SAMPLES

Heavy metal analysis was done at the Department of Geology, Makerere University using an Atomic Absorption Spectrometer (Agilent 240FSAA). The AAS was turned on and left to warm. After warming, calibration was done using known standards. After the calibration, each sample was then put and analysed separately and the concentration of each selected heavy metal contaminant recorded in mg/L (Ali *et al*., 2019).

3.7 DETERMINATION OF BIOACCUMULATION LEVELS

Bioaccumulation is the net uptake of a contaminant by an organism from the environment by all possible routes such as respiration, diet, dermal from any source such as water, sediment, and other organisms. Bioaccumulation factors (BAFs) were calculated in equation 1 as a ratio of the concentration level of the heavy metal or microplastic in fish muscles to concentration level of the heavy metal or microplastic in water (Environmental Protection Agency, 2002).

$$\mathrm{BAF} = \frac{C_{\mathrm{fish}}}{C_{\mathrm{water}}} \qquad (1)$$

Where C_{fish} is the concentration of metal in the fish tissues (mg/kg) and C_{water} is the metal concentration in the water (mg/L). The BAF values indicate the varying degrees of metal accumulation in different fish species. BAF > 1 indicates that the HM is accumulating in the fish at a higher concentration than in the water. This suggests that the fish has a tendency to accumulate the HM. BAF = 1 implies that the concentration of the substance in the fish is the same as in the water. In this case, the fish is not preferentially accumulating the HM. BAF <

1 suggests that the HM is not accumulating in the fish, or it is accumulating at a lower concentration compared to the water (Environmental Protection Agency, 2002).

3.8 HEALTH RISK ASSESSMENT

3.8.1 Estimated daily intake (EDI)

Health risks were calculated separately for adults and children using health risk models of the United States Environmental Protection Agency for both water and fish. Estimated daily intake (EDI, mg/kg/day) for fish was computed using equation 2 below

$$\mathrm{EDI} = \frac{\mathrm{C} \times \mathrm{FIR}}{\mathrm{WAB}} \times 10^{-6} \qquad (2)$$

Where;

C = heavy metal concentration; FIR is the fish ingestion rate, which is 55.5 g/day for adults and 52.5 g/day for children; WAB is average body weight: 70 kg for adults and 15 kg for children (United States Environmental Protection Agency, 2008)

3.8.2 Average daily dose

The average daily doses for water were calculated using equations 3 and 4 to establish exposure through direct ingestion ($\mathrm{ADID_i}$) in mg/kg/day and dermal contact ($\mathrm{ADID_d}$) in mg/kg/day) respectively (USEPA, 2008).

$$\mathrm{ADID_i} = \frac{\mathrm{C} \times \mathrm{WIR}}{\mathrm{WAB}} \qquad (3)$$

Where C = heavy metal concentration in $\mathrm{mgL^{-1}}$; WIR is the water ingestion rate, which is 858.9 mL/day for adults and 277.73 mL/day for children (United States Environmental Protection Agency, 2019); WAB is average body weight: 70 kg for adults and 15 kg for children (United States Environmental Protection Agency, 2008).

$$ADID_d = \frac{C \times SAF \times DAF \times ESA}{WAB} \times 10^{-6} \qquad (4)$$

Where C = heavy metal concentration in mgL^{-1}, ESA is exposed surface area (Adults: 5700 cm^2, Children: 2800 cm^2), DAF = dermal absorption factor (averagely 0.1% or 0.001) (United States Environmental Protection Agency, 2008), SAF = skin adherence factor (Adults: 0.07 $mg.cm^{-2}.day^{-1}$, Children: 0.2 $mg.cm^{-2}.day^{-1}$, $\times 10^{-6}$ $L.mg^{-1}$ is the correction factor so that ADD_i is in $mg.kg^{-1}.day^{-1}$ (Ahmed *et al*., 2022).

3.8.3 Target hazard quotient for non-carcinogenic risk assessment

The target hazard quotient was calculated for both direct ingestion of water (THQ_i) and fish (THQ_f), and dermal contact with water (THQ_d) (Equations 5, 6, and 7) respectively.

$$THQ_i = \frac{ADID_i}{R_f D_{oral}} \qquad (5)$$

$$THQ_d = \frac{ADID_d}{R_f D_{dermal}} \qquad (6)$$

$$THQ_f = \frac{EDI}{R_f D_{oral}} \qquad (7)$$

$R_f D_{oral}$ is the oral reference dose (Cr: 0.003, Cd: 0.001, Cu: 0.004 and Pb: 0.0035 $mg.kg^{-1}.day^{-1}$), $R_f D_{dermal}$ is the dermal reference dose (Cr: 0.003, Cd: 0.001, Cu: 0.003, Pb: 0.002$mg.kg^{-1}.day^{-1}$) (Fakhri & Alipour, 2021).

The cumulative risk (Total THQ) was considered as the arithmetic sum of the THQ values.

$$\text{Total THQ} = THQ_i + THQ_d + THQ_f$$

The risk to human health is considered low when the calculated THQ values are consistently below 1. When THQ values exceed 1, it indicates a potential health risk associated with exposure to heavy metals. The higher the THQ, the greater the potential risk (United States Environmental Protection Agency, 2008).

3.8.4 Carcinogenic health risk

The carcinogenic health risk (CHR) as incremental lifetime cancer risk for cancer-causing HMs (Pb, Cd, and Cr) was calculated as the product of $ADID_i$ and the cancer slope factor CSF in equations 8 and EDI and CSF in equation 9. The total cancer risk (Total TCR) was then calculated using equation 10 (Alidadi *et al*., 2019).

$$CHR_{ingest} = ADID_i \times CSF \qquad (8)$$

$$CHR_{EDI} = EDI \times CSF \qquad (9)$$

$$TCR = \quad CHR_{ingest} + CHR_{EDI} \qquad (10)$$

For Cr (CSF = 0.5 for ingestion, 20 for dermal), Cd (CSF = 6.1 for ingestion, 6.3 for dermal) and Pb (CSF = 8.5×10^{-2} for ingestion, 8.5×10^{-3} $kg.day.mg^{-1}$ for dermal).

A TCR value greater than 1 in a million (1×10^{-6}) indicates a potential elevated risk, while values less than this threshold are considered lower risk.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 MICROPLASTICS IN WATER AND FISH SAMPLES STUDIED

Like in the study by (Egessa *et al*., 2020) which found microplastics in water along the shores of L. Victoria, Uganda and (Yanuar *et al*., 2024) who found microplastics in spring water from Batu city in Indonesia, microplastics were prevalent in all the water and fish samples from the three study areas. Wairaka exhibits the highest concentration of microplastics in water (30±0.63 particles per liter) followed by Portbell (20±0.32 particles per liter) while Katosi had the lowest concentration of microplastics (14±0.41 particles per liter). This reflects varying degrees of dispersion through anthropogenic activity and natural factors at each site. This is in agreement with (Jambeck *et al.*, 2015) who found microplastics in Arctic Sea ice. Wairaka's higher concentration could be attributed to its proximity to industrial zones, leading to increased microplastic input into the water. Conversely, Katosi's lower concentration suggests less human impact, possibly due to its remote location. Portbell, situated between the other two sites, shows intermediate levels, indicating a mix of anthropogenic and natural influences. Across all sites, fish species exhibit higher mean concentrations of microplastics compared to the corresponding water samples. Studies by (Luo *et al*., 2014) reported microplastics in the gastrointestinal tracts of fish from both marine and freshwater environments indicating that fish and other marine organisms ingest microplastics, mistaking them for food. Portbell shows elevated levels of microplastics in fish species compared to Wairaka and Katosi. O. niloticus sampled at Portbell displays a mean concentration of 24.4±1.36 particles per kilogram, surpassing levels found at Wairaka (9±1.72 particles per kilogram) and Katosi (12±1.02 particles per kilogram). The higher microplastic concentration in fish from Portbell may result from increased exposure to contaminated waters or from microplastic disposal of plastic waste by human beings (Schymanski *et al*., 2021).

Table 1. Concentration of microplastics in water (particles/l) and fish (particles/kg)

Site	**Water**	***C. gariepinus***	***O. niloticus***	***L. niloticus***
Wairaka	30±0.63	12±1.41	9±1.72	8±1.24
Katosi	14±0.41	3±1.71	12±1.02	6±1.38
Portbell	20±0.32	13±1.12	24±1.36	9±1.59

The commonest morphotypes found were fibres, fragments and beads. Fibres are thin, elongated particles (D and E), fragments are broken or irregularly shaped pieces (A and B), while beads and pellets are oval or spherical (C) **(Figure 2)**. High-Density Polyethylene (HDPE) and Polyethylene (PE) were the most common types of plastic materials found. Polyvinyl Chloride (PVC) was also present in some samples. These can come from the breakdown of larger plastics, such as clothing fibres, plastic bags, and other plastic products. This is in agreement with (Yanuar *et al*., 2024) who analysed microplastics in spring water in Batu city, Indonesia.

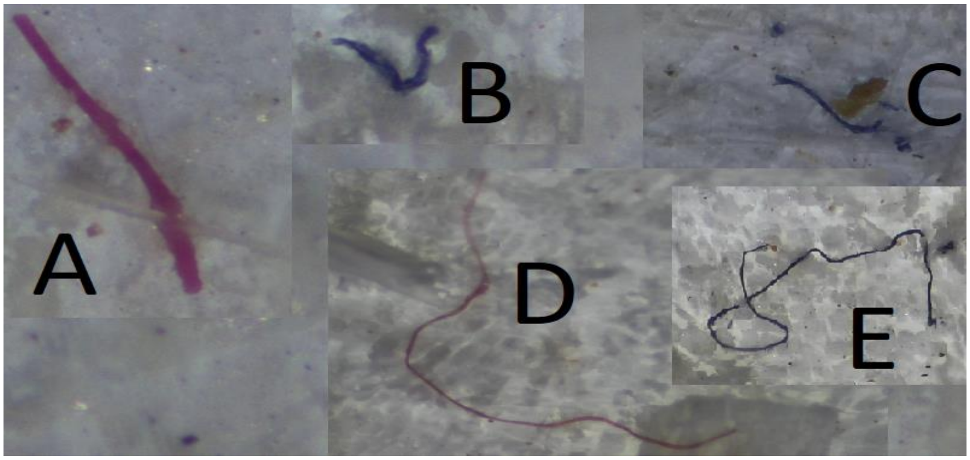


Figure 2. Types of microplastics in water and fish samples.

4.2 CONCENTRATION OF HEAVY METALS IN WATER AND FISH

Heavy metals were present in both water and fish samples studied from the three landing sites (**Table 2**). This is in agreement with (Fredrick, 2021) who found heavy metals in fish from Lake Victoria, Uganda and (Afzaal *et al*., 2022) who found heavy metals in water, sediments, and fish from rivers in Pakistan.

4.2.1 Heavy Metals in water

The concentration of chromium in water samples was above the WHO limit (0.05 ppm) at all the three landing sites. Wairaka had 0.12 ± 0.03, Katosi had 0.42 ± 1.37, while Portbell had 0.08 ± 0.05 ppm (**Table 2**). In their study of ecological risk assessment of heavy metals in surface sediments of six major Chinese freshwater lakes, (Ma *et al*., 2013) found out that chromium toxicity can result in health effects like respiratory problems, skin irritation, kidney damage, and liver dysfunction. Likewise, the concentration of cadmium was above the WHO allowable limit (0.005 ppm) at all the three landing sites. Wairaka had 0.01 ± 0.01, Katosi had 0.53 ± 1.38, while Portbell had 0.01 ± 0.01 ppm. In their study of heavy metals contamination in water, sediments and fish of freshwater ecosystems in Pakistan, (Afzaal *et al*., 2022) found out that cadmium toxicity can result in health effects, including respiratory problems, kidney damage, bone demineralization, cardiovascular issues, and cancer. The concentration of copper in water samples was below the WHO limit (1.50 ppm) across all the study sites. The concentration of lead in water samples was above the WHO allowable limit (0.05 ppm) at all the three landing sites. Wairaka had 1.46 ± 1.11, Katosi had 0.54 ± 0.79, while Portbell had 0.45 ± 0.51 ppm. This exposes the humans who use this water contaminated with lead to developmental delays, neurological damage, impaired cognitive function, cardiovascular issues, kidney damage, and reproductive problem according to (Ma *et al*., 2013).

4.2.2 Heavy metals in C. gariepinus

The concentration of selected heavy metals in C. gariepinus were below their WHO limits for all the three landing sites studied (**Table 2)**. This poses no health risks to both aquatic organisms and humans which is in agreement with (Adeyeye *et al*., 2013) in their study of heavy metal concentrations in some organs of African catfish from Eko-Ende Dam, Ikirun, Nigeria.

4.2.3 Heavy metals in O. niloticus

The concentration of chromium in O. niloticus is around the WHO limit (0.05 ppm) at Wairaka (0.05 ± 0.02) and Katosi (0.03 ± 0.01) with Portbell having a slightly higher concentration (0.28 ± 0.36 ppm) (**Table 2**). This poses no significant threat but there is need to monitor the concentration of chromium in water periodically in order to keep it below the allowable limit. This is in agreement with (Tibebe *et al*., 2019) who, in their study to determine heavy metals in tilapia and water samples from lake Hayq, Ethiopia found that the concentration of chromium was below the recommended limit by WHO. The concentration of copper, cadmium and lead were below the WHO limit at all the three landing sites except for lead at Portbell (0.56 ± 0.63 ppm) which was higher than the WHO limit (0.20 ppm). According to (Ishak *et al*., 2020) , in their study of lead and cadmium in tilapia fish from selected areas in Kuala Lumpur, exposure to low levels of lead can still be harmful to aquatic organisms due to bioaccumulation.

4.2.4 Heavy metals in L. niloticus

In L. niloticus, the concentration of copper (0.15 ± 0.02 ppm), lead (0.15 ± 0.01 ppm), chromium (0.06 ± 0.00 ppm), and cadmium (0.01 ± 0.01 ppm) across all the three landing sites studied were below their WHO permissible limits, (**Table 2)**. However, (Ishak *et al*., 2020) recommends that close monitoring be done to keep these levels below the WHO limits because these contaminants can still be harmful to aquatic organisms due to bioaccumulation.

Table 2. Concentration of Heavy Metals in water and fish samples and WHO limits

	Metal	Wairaka	Katosi	Portbell	WHO
Water	Cr (ppm)	0.12 ± 0.03	0.42 ± 1.37	0.08 ± 0.05	0.05
	Cd (ppm)	0.01 ± 0.01	0.53 ± 1.38	0.01 ± 0.01	0.005
	Cu (ppm)	0.02 ± 0.01	0.03 ± 0.01	0.07 ± 0.02	1.50
	Pb (ppm)	1.46 ± 1.11	0.54 ± 0.79	0.45 ± 0.51	0.05
C. gariepinus	Cr (ppm)	0.05 ± 0.00	0.03 ± 0.01	0.02 ± 0.02	0.05
	Cd (ppm)	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.05
	Cu (ppm)	0.13 ± 0.03	0.05 ± 0.03	0.06 ± 0.03	30.0
	Pb (ppm)	0.14 ± 0.02	0.13 ± 0.04	0.14 ± 0.04	0.20
O. niloticus	Cr (ppm)	0.05 ± 0.02	0.03 ± 0.01	0.28 ± 0.36	0.05
	Cd (ppm)	0.01 ± 0.00	0.01 ± 0.01	0.01 ± 0.00	0.05
	Cu (ppm)	0.06 ± 0.03	0.06 ± 0.01	0.04 ± 0.03	30.0
	Pb (ppm)	0.12 ± 0.02	0.17 ± 0.03	0.56 ± 0.63	0.20
L. niloticus	Cr (ppm)	0.06 ± 0.00	0.05 ± 0.00	0.02 ± 0.02	0.05
	Cd (ppm)	0.01 ± 0.01	0.01 ± 0.00	0.01 ± 0.00	0.05
	Cu (ppm)	0.15 ± 0.02	0.31 ± 0.36	0.03 ± 0.01	30.0
	Pb (ppm)	0.15 ± 0.01	0.13 ± 0.03	0.13 ± 0.02	0.20

The F-statistic (1.79) and the P-value (0.081), indicate that there is not enough statistical evidence that the observed differences in heavy metal concentrations among the sites is significant at the 0.05 level (**Table 3**). Although there are observable variations in concentration levels, these differences are not large enough to rule out the possibility that they occurred by chance. This suggests that the sites may have relatively similar contamination profiles with respect to heavy metals, or that the variation is too subtle to be detected given the current sample size or variability within groups. Future studies with larger sample sizes, more sensitive detection methods, or more frequent sampling may be required to better assess potential site-specific differences in heavy metal contamination.

Table 3. Analysis of Variance for heavy metal concentration in the selected fish

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3141.1	16	196.3	1.8	0.08	1.98
Within Groups	3404.5	31	109.8			
Total	6545.7	47				

4.3 BIOACCUMULATION AND TROPHIC TRANSFER OF CONTAMINANTS

4.3.1 Bioaccumulation of HM contaminants in fish species at Wairaka landing site

For chromium and copper, all the fish species had BAFs greater than 1 (**Table 4**). This, according to (Rajeshkumar & Li, 2018) and (USEPA, 2008) imply that chromium and copper are accumulating in all the three fish species. Cadmium and lead had their BAFs below 1 which indicated that cadmium and lead are not accumulating in any of the three fish species at Wairaka.

4.3.2 Bioaccumulation of HM contaminants in fish species at Katosi landing site

Our study revealed that chromium, cadmium, and lead had their BAF values below 1 for all the three fish species (**Table 4)**, indicating no bioaccumulation of these heavy metal contaminants in the studied fish species (USEPA, 2008). In contrast, copper displayed BAF values above 1 for all the fish species from Katosi landing site, suggesting significant bioaccumulation. the findings align with the previous research by (Shafiuddin *et al*., 2019) who found out that persistence of copper is attributed to the fact that copper is an essential element of the living tissue.

4.3.3 Bioaccumulation of HM contaminants in fish species at Portbell landing site

The study revealed that only chromium had its BAF values above 1 for all the three fish species (**Table 4**), indicating significant bioaccumulation of this heavy metal contaminant in the studied fish species (USEPA, 2008). In contrast, copper, cadmium, and lead displayed BAF values below 1 for all the fish species from Portbell landing site, suggesting no significant bioaccumulation (USEPA, 2008). Our findings align with the previous research by (Shafiuddin *et al*., 2019) who found out that cadmium and lead take long to accumulate, making their bioaccumulation relatively weak.

Table 4. Bioaccumulation factors (BAFs) for heavy metals in fish.

Site	**Species**	**BAFs**			
		Cr	**Cd**	**Cu**	**Pb**
Wairaka	*C. gariepinus*	3.87	0.22	6.21	0.27
	O. niloticus	3.28	0.36	3.26	0.24
	L. niloticus	4.23	1.02	8.29	0.29
Katosi	*C. gariepinus*	0.11	0.01	1.66	0.19
	O. niloticus	0.14	0.01	2.09	0.26
	L. niloticus	0.21	0.003	6.94	0.20
Portbell	*C. gariepinus*	1.42	0.63	0.97	0.31
	O. niloticus	21.81	0.71	0.73	0.49
	L. niloticus	1.34	0.63	0.56	0.29

4.3.4 Trophic transfer of microplastics

The highest BMF values are observed between L. niloticus (predator) and O. niloticus (prey) at the Wairaka site (BMF = 3.2), indicating significant biomagnification of microplastics in this predator-prey relationship (**Table 5)**. The Katosi and Portbell sites also show biomagnification but to a lesser extent compared to the Wairaka site. These observations are in line with previous findings by (Poste, 2010) which suggest that C. gariepinus persistently occupies the highest trophic level followed by L. niloticus while O. niloticus occupies the least trophic level. According to (Poste, 2010), C. gariepinus consistently occupies the highest trophic level (3.1), O. niloticus occupies the lowest trophic level (2.0) while L. niloticus occupies an intermediate trophic level (2.9).

Table 5. Biomagnification factors (BF) between the predator and prey

Site	Predator and Prey	BF
Wairaka	BF between *C. gariepinus* (pred) and *O. niloticus* (pr)	2.6
	BF between *L. niloticus* (pred) and *O. niloticus* (pr)	3.2
Katosi	BF between *C. gariepinus* (pred) and *O. niloticus* (pr)	1.0
	BF between *L. niloticus* (pred) and *O. niloticus* (pr)	1.4
Portbell	BF between *C. gariepinus* (pred) and *O. niloticus* (pr)	0.9
	BF between *L. niloticus* (pred) and *O. niloticus* (pr)	1.3

4.4 HEALTH RISK ASSESSMENTS

4.4.1 Non carcinogenic health risk assessment

From the study, all the total THQ values were way below 1 (**Table 6**). This indicates that there is no potential health risk associated with exposure to heavy metals through dermal contact and ingestion of both water and fish from Lake Victoria. These results align with the research findings by (Gnonsoro *et al*., 2022). However, the Total THQ values for Pb and Cd in children are higher than for other metals at all sites. This indicates that in the future, children face a higher potential health risk associated with exposure to heavy metals.

Table 6. Total target health quotient (THQ) in adults and children

Site	**Species**	**Total THQ × 10^{-5}**							
		Cr		**Cd**		**Cu**		**Pb**	
		Ad	**Ch**	**Ad**	**Ch**	**Ad**	**Ch**	**Ad**	**Ch**
Wairaka	*C. gariepinus*	3.0	19.0	7.9	51.0	3.2	19.0	86.0	560.0
	O. niloticus	2.9	18.0	8.7	52.0	2.9	18.0	86.0	560.0
	L. niloticus	3.0	19.0	8.1	52.0	3.3	20.0	1.9	560.0
Katosi	*C. gariepinus*	46.0	31.0	440.0	2900.0	4.4	28.0	110.0	720.0
	O. niloticus	46.0	31.0	440.0	2900.0	4.4	28.0	110.0	720.0
	L. niloticus	46.0	31.0	440.0	2900.0	4.6	29.0	110.0	720.0
Portbell	*C. gariepinus*	20.0	130.0	7.2	48.0	8.5	5.8	75.0	490.0
	O. niloticus	20.0	130.0	7.3	48.0	8.5	6.4	75.0	490.0
	L. niloticus	20.0	130.0	7.2	48.0	8.4	5.7	75.0	490.0

4.4.2 Carcinogenic health risk assessment

All results were above 1×10^{-6} but below 1×10^{-4} (**Table 7**). This indicates no potential risk of developing cancer due to ingestion of water and fish and dermal contact of water containing the selected heavy metal contaminants. These findings are also in agreement with the findings by (Gnonsoro *et al*., 2022) in their health risk assessment of heavy metals in hydro alcoholic gels of Abidjan, Côte d'Ivoire. The TCR values for children in Wairaka were generally high for all the fish species. This again indicates a potential future risk faced with the children and needs immediate intervention to keep the concentration of these heavy metal contaminants in check.

Table 7. Total cancer risk factor (TCR) from ingestion and dermal contact

Site	**Species**	**TCR × 10^{-4}**							
		Cr		**Cd**		**Cu**		**Pb**	
		Ad	**Ch**	**Ad**	**Ch**	**Ad**	**Ch**	**Ad**	**Ch**
Wairaka	*C. gariepinus*	50.0	230.0	36.0	160.0	-	-	24.0	100.0
	O. niloticus	45.0	200.0	56.0	250.0	-	-	21.0	92.0
	L. niloticus	250.0	250.0	160.0	730.0	-	-	25.0	110.0
Katosi	*C. gariepinus*	5.1	23.0	7.3	32.0	-	-	1.7	7.4
	O. niloticus	6.6	29.0	20.0	85.0	-	-	5.8	26.0
	L. niloticus	9.9	44.0	4.9	21.0	-	-	4.5	20.0
Portbell	*C. gariepinus*	3.6	16.0	20.0	85.0	-	-	4.8	21.0
	O. niloticus	55.0	240.0	22.0	96.0	-	-	30.0	130.0
	L. niloticus	3.5	15.0	21.0	85.0	-	-	4.3	19.0

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSIONS

The study found microplastics in both fish and water samples from all the tree landing sites. The commonest morphotypes found were fibres, fragments and beads. High-Density Polyethylene (HDPE) and Polyethylene (PE) were the most common types of plastic materials found. Polyvinyl Chloride (PVC) was also present in some samples. In water, Wairaka had the highest concentration of microplastics followed by Portbell and Katosi with 30±0.63, 20±0.32 and 14±0.41 particles per litre respectively. In fish, O. niloticus from Portbell had the highest microplastic concentrations for all three species, followed by Wairaka and then Katosi.

The selected heavy metal contaminants were also found in both fish and water samples. In water, lead (Pb) had the highest concentration observed at Wairaka site (1.46±1.10 ppm). Among the fish species, Nile Tilapia (O. niloticus) has the highest concentration of Copper (Cu) (0.13±0.03 ppm) at the Wairaka site.

The study also concluded that there is trophic transfer form lower trophic level to the highest. There was no evidence of developing cancer and other human health risks from ingestion and dermal contact of water and fish from Lake Victoria.

5.2. RECOMMENDATIONS

The study highlights significant environmental concerns regarding the presence of microplastics and heavy metals contaminants in L. Victoria, Uganda. The key points are:

Microplastic Pollution: All three landing sites showed high concentrations of microplastics in both water and fish. This indicates widespread plastic pollution.

Heavy Metal Contamination: Lead in water and copper in fish (particularly Nile Tilapia) were found in concerning concentrations, suggesting potential contamination that need to be addressed to protect aquatic ecosystems and public health.

Health Implications: Although the study found no immediate evidence of cancer or other health risks from dermal contact and ingestion, the presence of Microplastics and Heavy Metal contaminants warrants caution and preventive measures to safeguard both environmental and human health.

Trophic Transfer: The study indicates the trophic transfer of contaminants from lower to higher trophic levels, emphasizing the interconnectedness of the ecosystem and the potential for bioaccumulation of harmful substances.

Basing on the above findings, the study recommends the following:

1. Further research should involve extensive sampling to gain a clearer understanding of the factors contributing to heavy metal concentrations in these sites.
2. There is need for continuous monitoring and collaborative efforts to provide insights into temporal variations and trends in heavy metal contamination and microplastic pollution and safeguard the environment.

3. There is a need for proper waste management practices, plastic reduction initiatives, and to raise awareness about microplastic pollution.
4. Other exposure pathways and factors such as overall dietary habits and multiple contaminant exposures should be considered for a more accurate assessment of health risks.

REFERENCES

Adeyeye, A., Ayoola, P. B., & Adeyeye, A. (2013). Heavy metal concentrations in some organs of African catfish (Clarias gariepinus) from *Eko-Ende Dam, Ikirun, Nigeria. Continental Applied Sciences, 8*(1), 43–48. https://doi.org/10.5707/cjapplsci.2013.8.1.43.48

Afzaal, M., Hameed, S., Liaqat, I., Ali Khan, A. A., Abdul Manan, H., Shahid, R., & Altaf, M. (2022). Heavy metals contamination in water, sediments and fish of freshwater ecosystems in Pakistan. *Water Practice and Technology, 17*(5), 1253–1272. https://doi.org/10.2166/wpt.2022.039.

Akram, S., Najam, R., Rizwani, G. H., & Abbas, S. A. (2015). Determination of heavy metal contents by atomic absorption spectroscopy (AAS) in some medicinal plants from Pakistani and Malaysian origin. *In Pakistan Journal of Pharmaceutical Science 28*(5), 67-71.

Alava, J. J. (2020). Modeling the Bioaccumulation and Biomagnification Potential of Microplastics in a Cetacean Foodweb of the Northeastern Pacific: A Prospective Tool to Assess the Risk Exposure to Plastic Particles. *Frontiers in Marine Science, 7*(1). https://doi.org/10.3389/fmars.2020.566101

Ali, H., Khan, E., & Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. *In Journal of Chemistry, 17*(7), 37-42. Hindawi Limited. https://doi.org/10.1155/2019/6730305

Alidadi, H., Tavakoly Sany, S. B., Zarif Garaati Oftadeh, B., Mohamad, T., Shamszade, H., & Fakhari, M. (2019). Health risk assessments of arsenic and toxic heavy metal exposure in drinking water in northeast Iran. *Environmental Health and Preventive Medicine, 24*(1). https://doi.org/10.1186/s12199-019-0812-x

Aschner, J. L., & Aschner, M. (2005). Nutritional aspects of manganese homeostasis. *In Molecular Aspects of Medicine 26*(4), 353–362. https://doi.org/10.1016/j.mam.2005.07.003

Bayo, J., Olmos, S., & López-Castellanos, J. (2020). Microplastics in an urban wastewater treatment plant: The influence of physicochemical parameters and environmental factors. *Chemosphere, 238*(121), 245-251. https://doi.org/10.1016/j.chemosphere.2019.124593

Biginagwa, F. J., Mayoma, B. S., Shashoua, Y., Syberg, K., & Khan, F. R. (2016). First evidence of microplastics in the African Great Lakes: Recovery from Lake Victoria Nile perch and Nile tilapia. *Journal of Great Lakes Research, 42*(1), 146–149. https://doi.org/10.1016/j.jglr.2015.10.012

Chen, X. H., Zhou, H. B., & Qiu, G. Z. (2009). Analysis of several heavy metals in wild edible mushrooms from regions of China. *Bulletin of Environmental Contamination and Toxicology, 83*(2), 280–285. https://doi.org/10.1007/s00128-009-9767-8

Cole, M., Lindeque, P., Halsband, C., & Galloway, T. S. (2011). Microplastics as contaminants in the marine environment: A review. *In Marine Pollution Bulletin 62*(12), 2588–2597. https://doi.org/10.1016/j.marpolbul.2011.09.025

Dadebo, T. T., & Gelaw, G. T. (2024). Determination of metals in water samples within the irrigation area in Telo District, Kaffa Zone, and South Western Ethiopia. *Heliyon, 10*(7), 19-23. https://doi.org/10.1016/j.heliyon.2024.e29003

Egessa, R., Nankabirwa, A., Basooma, R., & Nabwire, R. (2020). Occurrence, distribution and size relationships of plastic debris along shores and sediment of northern Lake Victoria. *Environmental Pollution 7*(12), 257-261. https://doi.org/10.1016/j.envpol.2019.113442

Eriksen, M., Lebreton, L. C. M., Carson, H. S., Thiel, M., Moore, C. J., Borerro, J. C., Galgani, F., Ryan, P. G., & Reisser, J. (2014). Plastic Pollution in the World's Oceans: More than 5 Trillion Plastic Pieces Weighing over 250,000 Tons Afloat at Sea. *PLoS ONE, 9*(12), 23-28. https://doi.org/10.1371/journal.pone.0111913

Fakhri, Y., & Alipour, M. (2021). Refer to "Bioaccumulation and potential sources of heavy metal contamination in fish species in Taiwan: assessment and possible human health implications" by Vu et al. (2017). *In Environmental Science and Pollution Research, 28*(4), 4885 - 4886). Springer Science and Business Media Deutschland Gm bH. https://doi.org/10.1007/s11356-020-10679-2

Gaetke, L. M., & Chow, C. K. (2003). Copper toxicity, oxidative stress, and antioxidant nutrients. *In Toxicology, 189*(1–2), 147–163. Elsevier Ireland Ltd. https://doi.org/10.1016/S0300-483X (03)00159-8

Galloway, T. S., Cole, M., & Lewis, C. (2017). Interactions of microplastic debris throughout the marine ecosystem. *In Nature Ecology and Evolution, 1*(5). Nature Publishing Group. https://doi.org/10.1038/s41559-017-0116

Gnonsoro, U. P., Ake Assi, Y. E. D., Sangare, N. S., Kouakou, Y. U., & Trokourey, A. (2022). Health Risk Assessment of Heavy Metals (Pb, Cd, Hg) in Hydroalcoholic Gels of Abidjan, Côte d'Ivoire. *Biological Trace Element Research, 200*(5), 2510–2518. https://doi.org/10.1007/s12011-021-02822-y

Gouin, T., Roche, N., Lohmann, R., & Hodges, G. (2011). A thermodynamic approach for assessing the environmental exposure of chemicals absorbed to microplastic. *Envir onmental Science and Technology, 45*(4), 1466–1472. https://doi.org/10.1021/es1032025

Green, D. S., Boots, B., O'Connor, N. E., & Thompson, R. (2017). Microplastics Affect the Ecological Functioning of an Important Biogenic Habitat. *Environmental Science and Technology, 51*(1), 68–77. https://doi.org/10.1021/acs.est.6b04496

Hu, X., Wei, X., Ling, J., & Chen, J. (2021). Cobalt: An Essential Micronutrient for Plant Growth? *In Frontiers in Plant Science, 12*(1), 34-38. Frontiers Media S.A. https://doi.org/10.3389/fpls.2021.768523

Ishak, A. R., Zuhdi, M. S. M., & Aziz, M. Y. (2020). Determination of lead and cadmium in tilapia fish (Oreochromis niloticus) from selected areas in Kuala Lumpur. *Egyptian Journal of Aquatic Research, 46*(3), 221–225. https://doi.org/10.1016/j.ejar.2020.06.001

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R., & Law, K. L. (2015). Plastic waste inputs from land into the ocean. *Science, 347*(6223), 768–771. https://doi.org/10.1126/science.1260352

Järup, L. (2003). Hazards of heavy metal contamination. *In British Medical Bulletin, 68*(3), 167–182. https://doi.org/10.1093/bmb/ldg032

Khalid, N., Aqeel, M., Noman, A., Khan, S. M., & Akhter, N. (2021). Interactions and effects of microplastics with heavy metals in aquatic and terrestrial environments. *In Environmental Pollution, 290*(245). Elsevier Ltd. https://doi.org/10.1016/j.envpol.2021.118104

Khan, I., Aftab, M., Shakir, S. U., Ali, M., Qayyum, S., Rehman, M. U., Haleem, K. S., & Touseef, I. (2019). Mycoremediation of heavy metal (Cd and Cr)–polluted soil through indigenous metallotolerant fungal isolates. *Environmental Monitoring and Assessment, 191*(9). https://doi.org/10.1007/s10661-019-7769-5

Krewski, D., Yokel, R. A., Nieboer, E., Borchelt, D., Cohen, J., Harry, J., Kacew, S., Lindsay, J., Mahfouz, A. M., & Rondeau, V. (2007). Human health risk assessment for aluminium, aluminium oxide, and aluminium hydroxide. In Journal of Toxicology and Environmental Health – Part B: *Critical Reviews, 10*(1), 1–269. https://doi.org/10.1080/10937400701597766

Kubečka, J., Godø, O. R., Hickley, P., Prchalová, M., Říha, M., Rudstam, L., & Welcomme, R. (2012). Fish sampling with active methods. *In Fisheries Research, 123*(124), 1–3. https://doi.org/10.1016/j.fishres.2011.11.013

Linder, M., & Hazegh, M. (1996). Copper biochemistry and molecular biology. *Article in American Journal of Clinical Nutrition, 8*(2). https://doi.org/10.1093/ajcn/63.5.797

Liu, S., Shi, J., Wang, J., Dai, Y., Li, H., Li, J., Liu, X., Chen, X., Wang, Z., & Zhang, P. (2021). Interactions between Microplastics and Heavy Metals in Aquatic Environments: A Review. *In Frontiers in Microbiology, 12*(3). Frontiers Media S.A. https://doi.org/10.3389/fmicb.2021.652520

Lu, K., Zhan, D., Fang, Y., Li, L., Chen, G., Chen, S., & Wang, L. (2022). Microplastics, potential threat to patients with lung diseases. *In Frontiers in Toxicology, 4*(5), 35-39. Frontiers Media S.A. https://doi.org/10.3389/ftox.2022.958414

Luo, W., Verweij, R. A., & Van Gestel, C. A. M. (2014). Determining the bioavailability and toxicity of lead contamination to earthworms requires using a combination of phys icochemical and biological methods. *Environmental Pollution, 185*(1), 1–9. https://doi.org/10.1016/j.envpol.2013.10.017

Ma, Z., Chen, K., Yuan, Z., Bi, J., & Huang, L. (2013). Ecological Risk Assessment of Heavy Metals in Surface Sediments of Six Major Chinese Freshwater Lakes. *Journal of Environmental Quality, 42*(2), 341–350. https://doi.org/10.2134/jeq2012.0178

Miller, M. E., Hamann, M., & Kroon, F. J. (2020). Bioaccumulation and biomagnificat ion of microplastics in marine organisms: A review and meta-analysis of current data. *In PloS ONE, 15*(10). Public Library of Science. https://doi.org/10.1371/journal.pone.0240792

Mitra, S., Chakraborty, A. J., Tareq, A. M., Emran, T. Bin, Nainu, F., Khusro, A., Idris, A. M., Khandaker, M. U., Osman, H., Alhumaydhi, F. A., & Simal-Gandara, J. (2022). Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *Journal of King Saud University of Science and technology, 34*(3), 45-50. https://doi.org/10.1016/j.jksus.2022.101865

Mutter, J., Naumann, J., & Guethlin, C. (2007). Comments on the article "The toxicology of mercury and its chemical compounds" by Clarkson and Magos (2006). *In Critical Reviews in Toxicology, 37*(6), 537–549. https://doi.org/10.1080/10408440701385770

Naujokas, M. F., Anderson, B., Ahsan, H., Vasken Aposhian, H., Graziano, J. H., Thompson, C., & Suk, W. A. (2013). The broad scope of health effects from chronic arsenic exposure: Update on a worldwide public health problem. *In Environmental Health Perspectives*, *121*(3), 295–302). https://doi.org/10.1289/ehp.1205875

Needleman, H. (2004). Lead poisoning. In Annual Review of Medicine, 16(55), 209–222. https://doi.org/10.1146/annurev.med.55.091902.103653

OO, F. (2021). Study of Presence of Selected Heavy Metals in the Fish of Lake Victoria as a Predisposing Factor to Lifestyle Diseases in the 21st Century. *Food Science & Nutrition Technology, 6*(3), 1–12. https://doi.org/10.23880/fsnt-16000271

Prasad, A. S. (2013). Discovery of human zinc deficiency: Its impact on human health and disease. *In Advances in Nutrition, 4*(2), 176–190. https://doi.org/10.3945/an.112.003210

Qin, G., Niu, Z., Yu, J., Li, Z., Ma, J., & Xiang, P. (2021). Soil heavy metal pollution and food safety in China: Effects, sources and removing technology. *In Chemosphere, 267*(4), 78-89. Elsevier Ltd. https://doi.org/10.1016/j.chemosphere.2020.129205

Rajeshkumar, S., & Li, X. (2018). Bioaccumulation of heavy metals in fish species from the Meiliang Bay, Taihu Lake, China. *Toxicology Reports, 5*(2), 288–295. https://doi.org/10.1016/j.toxrep.2018.01.007

Rampley, C. P. N., Whitehead, P. G., Softley, L., Hossain, M. A., Jin, L., David, J., Shawal, S., Das, P., Thompson, I. P., Huang, W. E., Peters, R., Holdship, P., Hope, R., & Alabaster, G. (2020). River toxicity assessment using molecular biosensors: Heavy metal contamination in the Turag-Balu-Buriganga river systems, Dhaka, Bangladesh.

*Science of the Total Environment, 70*3(15), 234-247. https://doi.org/10.1016/j.scitotenv.2019.134760

Rochman, C. M., Hoh, E., Kurobe, T., & Teh, S. J. (2013). Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Scientific Reports, 3*(1), 5-8. https://doi.org/10.1038/srep03263

Sarkar, D. J., Das Sarkar, S., Das, B. K., Sahoo, B. K., Das, A., Nag, S. K., Manna, R. K., Behera, B. K., & Samanta, S. (2021). Occurrence, fate and removal of microplastics as heavy metal vector in natural wastewater treatment wetland system. *Water Research, 192*(5), 23-30. https://doi.org/10.1016/j.watres.2021.116853

Schwabl, P., Koppel, S., Konigshofer, P., Bucsics, T., Trauner, M., Reiberger, T., & Liebmann, B. (2019). Detection of various microplastics in human stool: A prospective case series. *Annals of Internal Medicine, 171*(7), 453–457. https://doi.org/10.7326/M19-0618

Schymanski, D., Oßmann, B. E., Benismail, N., Boukerma, K., Dallmann, G., von der Esch, E., Fischer, D., Fischer, F., Gilliland, D., Glas, K., Hofmann, T., Käppler, A., Lacorte, S., Marco, J., Rakwe, M. El, Weisser, J., Witzig, C., Zumbülte, N., & Ivleva, N. P. (2021). Analysis of microplastics in drinking water and other clean water samples with micro-Raman and micro-infrared spectroscopy: minimum requirements and best practice guidelines. *In Analytical and Bioanalytical Chemistry, 413*(24), 5969–5994. Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/s00216-021-03498-y

Shafiuddin Ahmed, A. S., Sultana, S., Habib, A., Ullah, H., Musa, N., Belal Hossain, M., Mahfujur Rahman, M., & Shafiqul Islam Sarker, M. (2019). Bioaccumulation of heavy metals in some commercially important fishes from a tropical river estuary suggests higher potential health risk in children than adults. *PLoS ONE, 14*(10), 5-9. https://doi.org/10.1371/journal.pone.0219336

Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. *In EXS, 101*(11), 133–164. https://doi.org/10.1007/978-3-7643-8340-4

Tibebe, D., Lemma, D., & Teshome, G. (2019). Determination of Heavy Metals in Tilapia (Oreochromis Niloticus) and Water Samples from Lake Hayq, South Wollo, *Ethiopia. International Journal of Chemistry and Materials Research, 7*(1), 10–19. https://doi.org/10.18488/journal.64.2019.71.10.19

Van Cauwenberghe, L., & Janssen, C. R. (2014). Microplastics in bivalves cultured for human consumption. *Environmental Pollution, 193*(6), 65–70. https://doi.org/10.1016/j.envpol.2014.06.010

Vincent, J. B. (2010). Chromium: Celebrating 50 years as an essential element? *In Dalton Transactions, 39*(16), 3787–3794. https://doi.org/10.1039/b920480f

Wright, S. L., Thompson, R. C., & Galloway, T. S. (2013). The physical impacts of microplastics on marine organisms: a review. *In Environmental pollution, 178*(7), 483–492. https://doi.org/10.1016/j.envpol.2013.02.031

APPENDICES

Appendix 1. Raw data for heavy metals from AAS

Lab No.	Sample No	Cr(mg/l)	Cd(mg/l)	Cu(mg/l)	Pb(mg/l)
1	WP1H	0.06	0.021	0.165	0.14
2	WP2H	0.059	0.013	0.151	0.15
3	WP3H	0.055	0.007	0.134	0.16
4	WC1H	0.05	0.003	0.118	0.13
5	WC2H	0.053	0.003	0.088	0.13
6	WC3H	0.055	0.003	0.133	0.16
7	WT1H	0.052	0.01	0.089	0.13
8	WT2H	0.054	0.003	0.05	0.14
9	WT3H	0.03	0.001	0.039	0.1
10	KP1H	0.051	0.001	0.048	0.12
11	KP2H	0.047	0.001	0.826	0.11
12	KP3H	0.052	0.005	0.052	0.17
13	KC1H	0.032	0.004	0.087	0.18
14	KC2H	0.023	0.005	0.031	0.12
15	KC3H	0.022	nd	0.032	0.09
16	KT1H	0.045	0.009	0.053	0.15
17	KT2H	0.029	0.004	0.059	0.21
18	KT3H	0.026	0.011	0.077	0.16
19	PT1H	0.03	0.01	0.026	0.14
20	PT2H	0.025	0.01	0.028	0.12
21	PT3H	0.775	0.008	0.074	1.41
22	PC1H	0.007	0.007	0.066	0.11
23	PC2H	0.037	0.008	0.069	0.19

24	PC3H	0.009	0.01	0.037	0.13
25	PP1H	0.001	0.01	0.046	0.12
26	PP2H	0.003	0.008	0.017	0.13
27	PP3H	0.048	0.007	0.035	0.15
28	KW11H	0.004	0.009	0.032	0.14
29	KW12H	nd	0.011	0.026	0.15
30	KW13H	nd	0.015	0.03	2.2
31	KW21H	nd	0.015	0.033	0.17
32	KW22H	nd	0.012	0.03	0.13
33	KW23H	0.027	0.012	0.031	0.12
34	KW31H	nd	4.56	0.026	1.56
35	KW32H	nd	0.033	0.015	0.19
36	KW33H	0.038	0.031	0.045	0.21
37	WW11	nd	0.017	0.012	1.19
38	WW12	nd	0.009	0.033	0.35
39	WW13	nd	0.008	0.033	0.78
40	WW21H	nd	0.009	0.031	0.14
41	WW22H	nd	0.011	0.003	0.53
42	WW23H	nd	0.014	0.01	5.7
43	WW31H	nd	0.014	0.009	0.16
44	WW32H	nd	0.014	0.023	4.52
45	WW33H	nd	0.023	0.038	0.13
46	PW11H	nd	0.021	0.039	0.14
47	PW12H	nd	0.01	0.056	0.14
48	PW13H	nd	nd	nd	nd
49	PW21H	nd	nd	0.024	0.32
50	PW22H	nd	0.01	0.071	0.15

51	PW23H	0.008	0.003	0.073	0.04
52	PW31H	0.103	0.011	0.059	1.53
53	PW32H	0.122	0.014	0.089	0.14
54	PW33H	0.081	0.017	0.066	0.56

Appendix 2. Raw data for Water Parameters

Sample	**Conductivity (μScm^{-1})**			**TDS (mg/L)**		
	R1	**R2**	**R2**	**R1**	**R2**	**R2**
WW1	673	690	670	359	360	356
WW2	679	691	672	361	363	359
WW3	676	680	679	349	351	350
KW1	693	687	689	360	361	364
KW2	682	680	681	363	366	365
KW3	671	681	675	353	369	357
PW1	683	691	673	342	341	348
PW2	677	682	688	322	329	325
PW3	689	688	692	319	320	318

Appendix 3. Raw data for Fish Parameters

Sample	**Length (cm)**			**Weight (g)**		
	1	**2**	**3**	**1**	**2**	**3**
WC	90	70	62	500	400	346
WT	30	32	29	300	321	298
WP	72	68	70	489	451	462
KC	51	48	62	241	233	276
KT	39	33	35	333	305	312
KP	92	71	63	503	412	356
PC	30	32	29	311	321	295
PT	51	48	62	240	230	270
PP	40	33	35	333	305	317

Appendix 4. Fish length and weights

Site	Specie	Length (cm)	Weight (g)
Wairaka	*C. gariepinus*	74.0 ± 12.10	415.3 ± 74.60
	O. niloticus	30.3 ± 1.20	306.3 ± 11.10
	L. niloticus	70.0 ± 2.00	467.3 ± 16.90
Katosi	*C. gariepinus*	53.7 ± 6.10	250.0 ± 20.40
	O. niloticus	35.7 ± 3.50	316.7 ± 13.90
	L. niloticus	75.3 ± 14.80	423.7 ± 71.80
Portbell	*C. gariepinus*	30.3 ± 1.20	309.0 ± 12.10
	O. niloticus	53.7 ± 6.10	246.7 ± 18.00
	L. niloticus	36.0 ± 3.90	318.3 ± 13.00

Appendix 5. Photos taken during sampling


LJRK-JJA025

Appendix 6. Water parameters

Parameter/Site	Wairaka	Katosi	Portbell
Temperature (ºC)	22.4 ± 0.20	22.6 ± 0.20	22.4 ± 0.30
pH	7.80 ± 0.10	7.67 ± 0.22	7.80 ± 0.08
Conductivity (μScm^{-1})	678.0 ± 7.40	681.1 ± 6.10	686.4 ± 6.20
TDS (mgL^{-1})	356.8 ± 4.40	361.4 ± 4.10	328.6 ± 9.90

Appendix 7. ADDi, ADDd (mg.kg-1.day-1), THQi of water, THQd, and CHRi

Site	Species	Cr		Cd		Cu		Pb	
		Ad	**Ch**	**Ad**	**Ch**	**Ad**	**Ch**	**Ad**	**Ch**
Wairaka	$ADD_i \times 0^{-9}$	0.2	0.3	0.2	0.3	0.2	0.3	6.4	9.6
	$ADD_d \times 0^{-11}$	7.8	51.2	7.8	51.2	10.3	67.6	296.4	19.0
	$THQ_i \times 10^{-9}$	56.7	83.3	17.0	25.0	55.0	85.0	18.9	27.4
	$THQ_d \times 10^{-5}$	2.6	17.1	7.8	51.2	2.6	16.9	84.7	55.6
	$CHR_i \times 10^{-9}$	0.1	0.2	1.2	1.8	-	-	0.5	0.8
Katosi	$ADD_i \times 0^{-9}$	3.0	4.5	9.4	14.2	0.4	0.6	8.2	12.4
	$ADD_d \times 0^{-11}$	18.2	90.5	48.0	29.0	17.2	12.4	38.9	25.0
	$THQ_i \times 10^{-9}$	10.0	15.0	94.0	14.0	10.0	15.0	23.9	35.9
	$THQ_d \times 10^{-5}$	46.1	30.2	48.0	29.0	4.3	28.1	19.1	71.6
	$CHR_i \times 10^{-9}$	1.5	2.3	57.3	86.6	-	-	0.7	1.1
Portbell	$ADD_i \times 0^{-9}$	1.3	1.9	0.2	0.2	0.7	1.1	5.6	8.4
	$ADD_d \times 0^{-11}$	58.7	38.5	7.2	47.4	33.6	22.0	29.9	17.0
	$THQ_i \times 10^{-9}$	43.3	63.3	16.0	20.0	17.0	27.0	16.0	24.0
	$THQ_d \times 10^{-5}$	19.6	12.2	7.2	47.4	8.4	5.5	74.3	48.3
	$CHR_i \times 10^{-9}$	0.7	1.0	1.2	1.2	-	-	0.5	0.7

Appendix 8. THQi of fish for the three landing sites.

Site	Species	$THQ_i \times 10^{-6}$							
		Cr		Cd		Cu		Pb	
		Ad	Ch	Ad	Ch	Ad	Ch	Ad	Ch
Wairaka	*C. gariepinus*	3.5	15.0	0.6	2.6	5.6	25.0	7.9	35.0
	O. niloticus	3.0	13.0	9.1	4.0	2.9	13.0	7.0	31.0
	L. niloticus	4.0	17.0	2.7	12.0	7.4	33.0	8.5	3.8
Katosi	*C. gariepinus*	0.3	1.5	0.1	0.5	0.5	2.2	0.6	2.5
	O. niloticus	0.4	1.9	0.3	1.4	0.6	2.8	1.9	8.7
	L. niloticus	0.7	2.9	0.1	0.4	3.1	13.5	1.5	6.6
Portbell	*C. gariepinus*	0.2	1.0	0.3	1.4	0.6	2.5	1.6	7.2
	O. niloticus	3.7	1.6	0.4	1.6	0.4	8.8	1.0	4.5
	L. niloticus	0.2	1.0	0.3	1.3	0.3	1.4	1.4	6.5

Appendix 9. EDI of fish in adults and children from the three landing sites

Site	Species	$EDI \times 10^{-9}$							
		Cr		Cd		Cu		Pb	
		Ad	Ch	Ad	Ch	Ad	Ch	Ad	Ch
Wairaka	*C. gariepinus*	10.43	46.03	0.59	2.63	22.40	98.88	27.75	122.50
	O. niloticus	8.99	39.67	0.91	4.03	11.77	51.98	24.46	107.98
	L. niloticus	11.96	50.75	2.69	11.90	29.73	131.25	29.73	131.25
Katosi	*C. gariepinus*	1.02	4.50	0.12	0.53	1.98	8.75	1.98	8.75
	O. niloticus	1.32	5.83	0.32	1.40	2.50	11.03	6.86	30.28
	L. niloticus	1.98	8.75	0.08	0.35	12.24	54.04	5.27	23.28
Portbell	*C. gariepinus*	0.71	3.12	0.32	1.40	2.26	9.98	5.67	25.03
	O. niloticus	10.97	48.44	0.36	1.58	1.70	7.53	35.28	155.75
	L. niloticus	0.69	3.03	0.34	1.40	1.31	5.78	5.03	22.23

Appendix 10. Cancer health risks from EDI

Site	Species	CHR from EDI × 10^{-3}							
		Cr		**Cd**		**Cu**		**Pb**	
		Ad	**Ch**	**Ad**	**Ch**	**Ad**	**Ch**	**Ad**	**Ch**
Wairaka	*C. gariepinus*	5.22	23.01	3.60	16.04	-	-	2.36	10.41
	O. niloticus	4.50	19.84	5.55	24.52	-	-	2.08	9.18
	L. niloticus	25.38	25.38	16.41	72.59	-	-	2.53	11.16
Katosi	*C. gariepinus*	0.51	2.25	0.73	3.23	-	-	0.17	0.74
	O. niloticus	0.66	2.92	1.95	8.54	-	-	0.58	2.57
	L. niloticus	0.99	4.38	0.49	2.14	-	-	0.45	1.98
Portbell	*C. gariepinus*	0.36	1.56	1.95	8.54	-	-	0.48	2.13
	O. niloticus	5.49	24.22	2.20	9.64	-	-	3.00	13.24
	L. niloticus	0.35	1.52	2.07	8.54	-	-	0.43	1.89