UNIVERSITY OF EMBU

FRANCIS KIGERA MIGWI

MSc

2020

MICROPLASTIC ABUNDANCE, COMPOSITION AND DISTRIBUTION IN THE ENDORHEIC LAKE NAIVASHA, KENYA

FRANCIS KIGERA MIGWI

A THESIS SUBMITTED IN PARTIAL FULFILMENT
FOR THE AWARD OF THE DEGREE IN MASTER OF SCIENCE IN
CHEMISTRY IN THE UNIVERSITY OF EMBU

OCTOBER, 2020

DECLARATION

This thesis is my original work and has not been presented in any other University for a degree award.

Signature………………………………… Date………………………………….

Francis Kigera Migwi

Department of Physical Sciences

B523/1127/2017

This thesis has been submitted for examination with our approval as the University supervisors

Signature………………………………… Date………………………………….

Dr. Joanne Ogunah

Department of Physical Sciences

University of Embu

Signature………………………………… Date………………………………….

Dr. John Kiratu

Department of Physical Sciences

University of Embu

DEDICATION

This work is dedicated to my father, Stephen Migwi, and my mother, Eunice Muthoni for providing me with the basis to advance in my studies. In loving memory of Sir Godfrey Mbuthia Kigera, continue resting well dad.

ACKNOWLEDGEMENT

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA   Analysis of Variance

ATR-FTIR   Attenuated Total Reflectance- Fourier-Transform Infrared Spectroscopy

BPA   Bisphenol A

CDCP   Center for Disease Control and Prevention

DDTs   Dichloro-diphenyl-trichloroethanes

DO   Dissolved Oxygen

d.w   Dry Weight

GBM   Green Belt Movement

GESAMP   Group of Experts on the Scientific Aspects of Marine Environmental Protection

GoK   Government of Kenya

KMFRI   Kenya Marine and Fisheries Research Institute

KNCO   Kenya Network of Cancer Organization

NEMA   National Environment Management Authority

NTU   Nephelometric Turbidity Units

PBDEs   Polybrominated Diphenyl Ethers

PBTs   Persistent, Bio-accumulative and Toxic compounds

PCBs   Poly-Chlorinated Biphenyls

PE   Polyethylene

PES   Polyester

PET   Polyethylene Terephthalate

pH   Potential of Hydrogen

POPs   Persistent Organic Pollutants

PP   Polypropylene

PVC   Polyvinylchloride

SAPEA   Science Advice for Policy by European Academies

TDS   Total Dissolved Solids

TN   Total Nitrogen

TP   Total Phosphorus

WWTP   Wastewater Treatment Plant

ABSTRACT

Plastic pollution has recently gained global concern due to the negative effect it presents on both the environment and human health. In the environment, plastics degrade yielding millions of micro- and nano-scale plastic particles. The microplastics have the ability to adsorb organic pollutants, heavy metals, and micro-organisms in either the aquatic or terrestrial environments. The microplastics size range and ubiquity in the environment provides an easy pathway into the food chain through ingestion, bio-accumulation and bio-magnification. This study was conducted with an aim of determining the abundance and composition of microplastic particles in Lake Naivasha surface waters and sediments. The study also entailed the evaluation of the possible physical chemical parameters that could affect the distribution of microplastic within the lake. Volume reduced and bulk sampling methods were used to collect samples of floating debris in surface waters and sediments respectively. The physical chemical parameters were measured *in situ* whereas the nitrogen and phosphorus nutrient levels were determined in the laboratory. Density separation using concentrated brine solution and wet peroxide oxidation methods were used for microplastics extraction. The recovered particles were analyzed using microscopy for physical characteristics (shape and color) while the microplastics chemical composition was determined using Fourier-transform infrared spectroscopy (FTIR). All the physical-chemical parameters in the sampled locations of Lake Naivasha exhibited significance differences ($p<0.05$) except salinity. These differences were attributed to the infestation by water hyacinth (lower dissolved oxygen and temperatures), originality of the lake (pH and total dissolved solids), and anthropogenic activities (higher turbidity, conductivity and nutrient levels). The average microplastic concentration was found to be 0.407 ± 0.135 particles/m^2 and 177.3 ± 87.4 particles/kg in surface waters and surface sediments respectively. The post-hoc Tukey Honest Significance Difference test exhibited significant differences ($p<0.05$) in the microplastics abundance in the studied locations of the lake. The highest microplastic levels were recovered in the lakes' major inflow, River Malewa. The high variability in the microplastic densities exhibited between the sampled locations was attributed to human activities, water and wastewater intake through rivers and tributaries, and the presence of local wind patterns responsible for the general water circulation. Colored and non-colored microplastics, of shapes categories fragments, fibers and films were identified and were majorly composed of polypropylene, polyethylene, and polyester in surface waters, whereas polyethylene terephthalate, polyvinylchloride and nylon polymers were dominant in the surface sediments. The lakes' dominating abundance of fibrous, fragmented and colored (83%) microplastics was an indication that secondary microplastics were the major source of pollutants in the lake. Moreover, correlational analysis done exhibited a strong positive existing association between microplastic quantities and turbidity, total nitrogen, and total phosphorus in Lake Naivasha surface waters. Thus, this study concludes that the microplastic pollution in Lake Naivasha is contributed by anthropogenic activities with the distribution drivers being related to the nutrients and turbidity levels of the lake. This study recommends on the improvement on microplastic waste management around rivers and lakes by local authorities and the National Environment Management Authority (NEMA), and increase in the public awareness and education.

CHAPTER ONE

INTRODUCTION

1.1 Background

Lake Naivasha is a freshwater lake located in the Eastern Rift Valley, Kenya. The lake lies at latitude 0° 45' South, and longitude 36° 20' East. It has an altitude of 1,890 m above sea level, covering an approximate surface area of 139 km^2. It is fed by the perennial River Malewa (90% of freshwater inflow), from the Nyandarua and Kinangop mountain ranges as the main catchment areas, and the rest supplied by the Gilgil and Karati Rivers (Mutia *et al*., 2012). It is the second largest freshwater lake and an important economic asset for Kenya. Lake Naivasha is unique since it is found as the only freshwater ecosystem lying in an otherwise series of saline lakes in the East African Rift Valley (Everard *et al*., 2002). Currently, the lake supports an increasing population, together with industries such as tourism, geothermal energy production, and floriculture farms (Mutungwa, 2011).

In 1995, Lake Naivasha was established as one of the wetland sites of international importance in Kenya, providing for national and international cooperation on wetlands conservation and the sustainable use of resources (Njiru *et al.*, 2017). However, the lake is threatened by extensive anthropogenic activities in its catchment, including the discharge of untreated effluents from industries, horticulture farms and human settlements. Similarly, the lake receives contaminated inflow from rivers channeling from its overlying catchment areas where crop and animal farming is practiced (Mutia *et al*., 2012). Beside these activities, tourist activities, fishing, laundry and the discharge of plastic contaminated wastewater into the lake are also contributors to the lakes' plastic pollution (Lots *et al*., 2017; Andrady, 2011), despite Kenya introducing one of the world's harshest plastic bags ban in August 2017 (Oguge, 2019). Additionally, the lake is prone to large water fluctuations as a result of its shallowness (mean depth of 6 m), and the long dry seasons and hot periods that increase the evaporation rates (Kamau *et al*., 2008). This has led to recent declines in lake level and water quality, in turn leading to a marked increase in scientific studies, in this case the microplastic pollution, with a

common goal of improving the lakes' management and conservation (Ogendi *et al*., 2014).

Plastics are incredible, all-round materials that have been shown to possess robust thermal and electrical insulation properties, while being inexpensive, light, strong, durable, corrosion-resistant (Andrady, 2011). They are however prone to degradation by either weathering or disintegration in the environment resulting in their surface embrittlement and micro cracking to form microplastics (Andrady, 2017). Microplastics are small (less than 5 mm in diameter) materials, that consists of a vast spectrum of synthetic or semi-synthetic malleable organic compounds and particles ubiquitous in the environment (Tagg *et al*., 2015). They include a diverse range of polymer types like polypropylene, polyester, polystyrene and polyethylene, with shapes like beads, pellets, films, fibers, and fragments.

The microplastic sources can be either, primary sources which include production pellets, synthetic fabrics and cosmetics, or secondary sources which include plastic particles in the micro-size domain, that have resulted from the degradation, disintegration and fragmentation of the larger-sized plastic items (Andrady, 2011). Microplastics presence has been reported in surface layers of water bodies (Fischer *et al*., 2016; Free *et al*., 2014; Eriksen *et al*., 2013) as well as in lake and river sediments (Peng *et al*., 2017; Qiu *et al*., 2015; Browne *et al*., 2011). The human density and activities around the water bodies has been widely observed to influence the composition of microplastics present (Dris *et al*., 2018). However, information on microplastic prevalence in Lake Naivasha is still unknown.

Planktonic organisms residing in aquatic environments were previously not known to be threatened by the large plastic debris (Van Cauwenberghe *et al*., 2013). However, the recovery of industrial pellets from biofouling organisms of Sargasso Sea was the first indication of interaction between aquatic organisms and microplastics. This illustrated the potential ecological and human health risks that microplastics may present, especially due to their similar small size range (GESAMP, 2015). To date, microplastics ingestion and accumulation by aquatic species ranging from zooplankton to fish has been widely reported and documented (Frias, *et al.*, 2014; Kosore *et al*., 2018; Rochman *et al.*, 2013;

2

Scherer, *et al.*, 2018). This implies that microplastics have found their way into the marine food web and could impact heavily on food safety and human health. These pollutants may also act as vectors for toxic chemicals transportation, which may originate from either the surrounding aquatic environment (persistent organic pollutants), or directly from the plastic material (additives and by-products) (GESAMP, 2015). Moreover, the detection of microplastics in human consumption products such as table salt and bottled drinking water has triggered public concerns on their presence and health risks (Peixoto *et al*., 2019; Pivokonsky *et al*., 2018; Yang *et al*., 2015).

The existing environmental conditions determine the degradation rate and pattern that microplastics undergo in any ecosystem. These incudes processes such as; mechanical degradation by wind action and sand friction (Zbyszewski, *et al.*, 2014), oxidative weathering from ultra-violet radiation exposure and action of hydrogen degrading microbes that cause biological degradation (Anderson, *et al.,* 2002). Although photo-oxidative degradation is reduced by incorporation of stabilizers during plastic production, disintegration has been shown to be facilitated by variation of temperatures and coverage with either water and/or sediment, reducing the ultra-violet radiation exposure (Duis and Coors, 2016). This study therefore focuses on the spatial variations of selected physical-chemical parameters to aid in determining the microplastics distribution drivers that are still unknown in Lake Naivasha.

Although there are numerous in-depth studies that have been conducted on microplastics in the marine ecosystems, only a limited number of studies have focused on freshwater bodies. As such, knowledge on microplastics pollution, particularly in lakes and rivers which are potential sources and/or transport pathways, is still limited. Freshwater ecosystems, being closely connected to microplastics origins, have been pointed out as the common passageways of microplastics transfer into oceans (Dris *et al*., 2018). Comparably, similar and/or higher microplastics quantities have been documented in lakes of different locations and dimensions (Eriksen *et al*., 2013; Fischer *et al*., 2016). Thus, given the limited data on microplastics pollution in freshwater ecosystems and especially in Africa, there is need to better characterize the presence, distribution drivers, and the potential sources of microplastics into freshwater ecosystems. This will help to

exhaustively evaluate the microplastics pollution risk, and consequently develop and enact effective measures to address this emerging menace.

1.2 Statement of the problem

The low cost of production, bio-inertness and portability has made plastics to be extensively used in the delivery of quality modern lifestyles (Andrady, 2011). This has led in the intensive growth of plastic production and consumption rates. However, due to the poor plastic waste management and disposal mechanisms employed and mostly in Africa, they find their way into the environment where they are affected by either terrestrial or aquatic environmental conditions. This results in the large plastic debris disintegration in systems such as garbage disposal sites and wastewater treatment plants (WWTPs) which finally ends up into the aquatic ecosystems as microplastic particles (Yokota *et al.*, 2017). Characterized by a large surface area-to-volume ratio, microplastics have the ability to accumulate water-borne pollutants such as heavy metals and persistent, bio-accumulative and toxic compounds (PBTs) on their surfaces (Ashton, *et al.,* 2010; Koelmans, *et al.,* 2013). Subsequently, their size ranges allows for their easy ingestion, together with their adsorbed contaminants, by aquatic species and are indirectly propagated up the aquatic food web through the predator-prey trophic transfer mechanisms. In the higher trophic levels, microplastics can leach either the adsorbed hydrophobic contaminants and/or their inherent toxic monomers facilitated by the presence of digestive fluids and/or favorable pH and temperatures (Talsness *et al.*, 2009). On desorption, these have negative health effects including direct metal toxicity, carcinogenicity, and endocrine disruption which can lead to cancers, birth defects, children developmental problems and immune system suppression (CDCP, 2009). Lake Naivasha, a source of food and freshwater, has recently been characterized by water fluctuations because of the low rainfall experienced and the high evaporation rates that occur during the hot dry periods (Kamau *et al*., 2008). This has led to the concentration of pollutants in the lake water, sediments and biota, culminating in the deterioration of the lakes' water quality (Mutia *et al*., 2012). Similarly, anthropogenic activities such as fishing, tourism, household/industrial waste disposal into the lake, and transport through the inflow of contaminated rivers and tributaries have been reported to result in the increased lakes' pollution (Ndungu *et al*., 2015). Further, these activities have been

shown to contribute to the plastics and microplastics presence in inland freshwater ecosystems (Dris *et al*., 2018), and thus forming a baseline for microplastics and water quality assessment in this study.

1.3 Justification of the study

Plastic debris has been and is still a global concern that threatens both the aquatic biota and ecosystem (Clark *et al*., 2016). Due to the diverse environmental factors found in aquatic ecosystems, the debris disintegrates yielding plastic particles in the micro-scale size range (Koelmans *et al*., 2014). These microplastics are characterized by a vast variety of material densities, shapes, and particle sizes that make them able to accumulate toxic ingredients like the hydrophobic persistent organic pollutants (POPs), residual plastic monomers, nutrients, additives and heavy metals from the surrounding (Yokota *et al*., 2017; Vandermeersch *et al*., 2015). This renders interactions with biota via multiple pathways easily possible. Subsequently, there is increased biological, chemical, and physical health risks on aquatic species that ingest them directly and also on those in the higher trophic levels (Scherer *et al*., 2018). Microplastics ingestion has been reported in diverse aquatic species ranging from zooplankton to fish. These reports have triggered concerns on the prospect of microplastics to accumulate in the aquatic food chain, and the subsequent effects they could present on the overall food safety and human health (GESAMP, 2015; Vandermeersch *et al*., 2015). Among the harmful effects of microplastics to human population is the ability of the adsorbed toxic ingredients to cause cancer (CDCP, 2009), which according to the Kenya Network of Cancer Organization (KNCO), is the third highest cause of mortality in Kenya (GoK, 2010). However, most studies conducted on microplastics have focused majorly on marine ecosystems with freshwater microplastic studies still at an early stage and especially in Africa. Thus, due to the high dependency of the lake as a water and food source, together with the increasing concentration of nutrients and heavy metals that has been reported in Lake Naivasha over the years, this research anchors on the assessment of the extent, sources, and distribution factors of microplastics in the lake. This will aid in the development of suitable and sustainable policies and management tools by the environmental protection agencies such as NEMA, under the overall objective of addressing this emerging contaminant threat.

1.4 Hypothesis

i. The physico-chemical parameters and nutrient levels of Lake Naivashas' surface water are not significantly different among the seven selected locations.

ii. There is no variation of the microplastic abundance in the seven selected locations of Lake Naivasha.

iii. There is no significant difference in the microplastic compositions present in the seven selected locations of Lake Naivasha.

1.5 Objectives

1.5.1 General objective

To determine the composition, abundance, and distribution of microplastics within Lake Naivasha

1.5.2 Specific objectives

i. To determine the physico-chemical parameters and nutrient levels of surface waters in the seven selected locations of Lake Naivasha.

ii. To determine the abundance of microplastics present in Lake Naivasha surface water and surface sediments.

iii. To determine the composition of microplastics present in Lake Naivasha surface water and surface sediments.

CHAPTER TWO

LITERATURE REVIEW

2.1 Plastic pollution

Plastics are a set of polymers that are composed of polymerized monomers that are designed and structured to satisfy the properties to fit different usages (Andrady and Neal, 2009). However, during polymerization reaction, traces (0.0001-4%) of residual toxic monomers are left in the plastic matrix (Araújo *et al*., 2002). Similarly, polymerization involves the incorporation of a wide spectra of substances (additives/stabilizers) aimed at enhancing the plastic properties and performance (Geyer *et al*., 2017). The additives can either be low molecular, polymeric, organic or inorganic substances. Such include ultra-violet (UV) stabilizers to prevent plastic degradation by effect of sunlight, plasticizers to improve on the material flexibility/plasticity and inorganic fillers meant to strengthen the plastic material (Geyer *et al*., 2017). Colorants and flame retardants are also added to increase and improve the plastics physical properties such as color and flame resistivity respectively (Andrady and Neal, 2009). As such, plastics' spectrum of usage increases making them impartible in the delivery of comfort, safety and quality in modern-day lifestyles.

Since the inception of plastics in the mid-20th century, the plastics production and consumption rates have greatly increased. For instance, the plastic production has seen a tremendous increase from 1.7×10^6 tons in the 1950s, to 3.2×10^8 tons in 2015 (PlasticsEurope, 2016). Similarly, the past 10 years have been reported to account for more than 2.6 billion metric tons of plastic production worldwide (Clark *et al*., 2016). Subsequently, this has culminated in an intensive plethora of plastic waste generation and discharge into our aquatic and terrestrial environments. By 2015, an estimative 6.3×10^9 metric tons of plastic waste is believed to have been produced, with only 9% being recycled (Geyer *et al*., 2017).

In Africa, inadequacy of waste collection services has led to 90% of the generated waste being disposed in either uncontrolled or controlled dumpsites, and only 4% waste recycled (Geyer *et al*., 2017). Additionally, there is limited awareness of the general public on waste separation and recycling practices, resulting in large plastic debris

degradation through processes such as garbage disposal plants and waste water treatment plants (Toumi *et al*., 2019). In Kenya, the Green Belt Movement (GBM) reported that over 24 million plastic bags were used monthly in 2013, with almost half of this ending up in the solid waste mainstream and consequently into the aquatic ecosystem (GBM, 2014). This has resulted in many countries banning the production, use, and importation of plastic bags, and in Kenya, this law took effect in 2017 (Oguge, 2019). However, these laws suffered from poor implementation and as a result, plastic pollution is and remains to be a threat, especially in the urban areas.

Plastic contamination has therefore become a growing environmental problem in both terrestrial and aquatic ecosystems globally. Beside climate change, plastic pollution is recognized as an emanating threat, capable of affecting the future human ability to preserve the biological heterogeneity (Sutherland *et al*., 2011). For instance, marine debris, a contributor to biodiversity loss, comprises of 75% plastic of the shoreline debris recorded worldwide (Eerkes-Medrano *et al*., 2015), a result fuelled by their high production rates and durability making them ubiquitous in the environment.

2.2 Microplastics as an emerging threat contaminant

Being non-biodegradable, plastic persistence in the environment is a major concern (Andrady, 2011). However, whether floating in surface waters, wrecked on shores and beaches, or in terrestrial environments, plastics exposure to environmental variables leads to fragmentation and disintegration yielding microplastics. This mechanisms yield is the major contributor of microplastics in our aquatic environments and is classified as secondary source of microplastics origin. Similarly, microplastics are derived from plastics manufactured in the micro-size scale. Their usage spectrum is varied to raw materials of plastic production, personal care and cosmetics production, being composed of pellets, granules, beads and plastic powder (Andrady, 2011; Fendall and Sewell, 2009).

With the intensive growing knowledge on their scale and magnitude of pollution, concerns about microplastics presence and effects on aquatic biota and consequently on the human health have increased (SAPEA, 2019). Unlike conventional environmental pollutants, microplastics originating from either primary or secondary sources varies

greatly with respect to chemical composition, color, shape, size, and specific density (Duis and Coors, 2016). As such, microplastics have gained different definitions from different authors with respect to these properties. Taking into account all these definitions, Frias and Nash, (2019) found a consensus on the microplastic definition as "*any synthetic polymeric matrix or solid particle, regularly or irregularly shaped, with size range (1μm-5mm), of either primary or secondary manufacturing origin, and which is insoluble in water*".

The diversity in the microplastic physical and chemical compositions increases the complexity for potential analysis of toxicity posed by the chemicals found in the plastic matrix. As earlier mentioned (Section 2.1), plastic production involves polymerization of many different monomers and the incorporation of a broad range of additives that are aimed at increasing and/or improving the plasticity and polymer characteristics. However, the polymeric compounds (monomers) and additives used in plastic production are toxic. For instance, polyvinylchloride polymer production employs phthalates and bisphenol A (BPA) plasticizers to reduce thermal and photo-degradation (Li *et al.*, 2018). Similarly, the flame retardants and colorants used in production bio-accumulate in human bodies, with their toxic compounds being known to be endocrine disruptors. Besides, BPA, phthalates and Polybrominated Diphenyl Ethers (PBDEs) additives have been confirmed in humans (Talsness *et al.*, 2009). Some colorants used in plastic production may also contain heavy metals which are susceptible to discharge from the plastic matrix into either the aquatic system or the food web causing toxins bio-accumulation in biota (Ernst *et al.*, 2000).

Microplastics are characterized by a large surface area-to-volume ratio and intrinsic hydrophobicity. Therefore, highly toxic and persistent pollutants in the environment (such as, DDTs, PCBs, and heavy metals) can be sorbed onto their surfaces. Microplastics have been shown to sorb organic pollutants with large partitioning coefficients range of up to 10^4-10^6 (Andrady, 2017; Holmes *et al.*, 2014; Mato *et al.*, 2001). The aforementioned pollutants sorbed on microplastic surfaces can be released inside an organisms' body where the pH is lower, temperatures are higher, and the

digestive fluids are available. These factors have been confirmed to substantially accelerate the desorption rate in organisms than in water (Bakir *et al*., 2014).

Equally, microplastics threat is compounded to their durability and persistency than any other media in the aquatic environment. For instance, under optimal lab exposure conditions, a polythene polymer transforms only 0.1% of its carbon into carbon (IV) oxide per year. As such, they have the potential to geographically transfer microorganisms which colonize their surfaces (Thiel and Gutow, 2005). For example, wastewater associated pathogenic organisms could also find their ways into waterways through attachment of the organism onto microplastics. On this account, microplastics associated bacteria were confirmed by the presence of pathogens on recovered microplastics in Yangtze estuary, China (Jiang *et al*., 2018). However, microplastics remain understudied in freshwater ecosystems unlike the in-depth studies that have been conducted in marine ecosystems.

2.3 Microplastics and water physico-chemical parameters

Microplastics presence has been reported in most of the marine habitats and there is growing documentation of their presence in freshwater systems across the world. Their physical and chemical composition, together with the environmental conditions have been reported to significantly affect their distribution (Van Cauwenberghe, *et al.*, 2015). The microplastics distribution is associated with variations of environmental parameters including but not limited to temperature, pH, salinity, turbidity and electrical conductivity (Lima *et al*., 2015; Lima *et al*., 2014). For instance, in Goiana estuary, salinity presented an increasing trend upstream, with temperature showing a seasonal trend in the upper and middle estuaries. This was experienced in the late rainy season that recorded the highest microplastic abundance (Lima *et al*., 2014). Although the microplastic abundance and distribution has been reported to be affected by environmental conditions (Klein *et al*., 2015; Lima *et al*., 2015, 2014; Turra *et al*., 2014), there is limited information showing the direct variation of microplastic particles with environmental variables. Due to the huge water abstractions by increasing population around the lake together with climate change effects, the water quality of Lake Naivasha has been reported to be changing (Mutungwa, 2011; Stoof-Leichsenring

et al., 2011; Ndungu *et al*., 2015). Therefore, this study aimed at establishing the quantities and composition of microplastics found under the dynamic range of environmental conditions in Lake Naivasha.

Nutrients level is an important quality parameter to consider, as it affects the quality of water (Yan *et al*., 2016), and subsequently the abundance and composition of microplastics in a given aquatic environment. Nitrogen is an important element in the plant and animal tissue production being primarily used by both for protein synthesis. Phosphorus on the other hand is an essential nutrient for the conversion of sunlight into usable energy, cellular growth and reproduction. However, in excessive amounts, these primary nutrients pollute the aquatic environment, (Fageria, 2016). For instance, nitrogen at elevated levels, presents a great risk on the health of humans (mostly infants) and animals. On the other hand, phosphorus that is majorly contributed by anthropogenic activities causes abnormal algae growth and the degradation of lake water quality (Schoumans *et al*., 2014). Besides, the high nutrient levels have been reported to result in increased biological degradation through increased hydrogen degrading microbes activity (Anderson *et al*., 2002).

Lake Naivashas' water input is dependent on the inflow from the three main rivers (Malewa, Karati, and Gilgil), ground water recharge and precipitation. On the other hand, the lakes outflow is function to ground water seepage, evapotranspiration and anthropogenic water abstractions (Kamau *et al*., 2008; Ndungu *et al*., 2015). Large water abstractions have been linked to water used in irrigation of the emergent horticultural farms, geothermal power production, and domestic uses by the rapid informal settlements. Similarly, the upstream changes in land use have led in reduced inflows and agrochemicals pollution thus increasing pressure on the ecosystem (Ndungu *et al*., 2015). These factors have caused high contamination levels by heavy metals and nutrients, and their concentration increase has been recorded over the years (Kamau *et al*., 2008; Stoof-Leichsenring *et al*., 2011; Ndungu *et al*., 2015). This study therefore focuses on analysis of these essential nutrients in the surface waters, to establish whether or not, there exists a relationship with the microplastic quantities reported.

2.4 Microplastics abundance in aquatic environments

Microplastics have been reported in surface waters and sediments of lakes, rivers and oceans globally. In surface waters and sediments, microplastics abundance has been reported to vary by a factor of 10^3 across the different sampled regions and locations (Dris *et al*., 2018). In freshwater ecosystems, microplastics presence has been documented in the surface waters of lakes such as the Laurentian Great Lakes (0.043 items/m^2; Eriksen *et al*., 2013), Asiatic lake Hovsgol (0.02 items/m^2; Free *et al*., 2014), and European lakes Geneva and Maggiore (0.22 items/m^2, Faure *et al.*, 2015). Moreover, microplastics have been detected in benthic sediments from Asia (Peng *et al.*, 2018; Wang *et al*., 2017), America (Zbyszewski *et al*., 2014), and Europe (Horton *et al*., 2017; Klein *et al*., 2015; Vaughan *et al.*, 2017). Similarly, microplastics have been reported in African aquatic ecosystems such as the South African coastline surface waters (257-1215 items/m^3) and sediments (688-3308 items/m^2; Nel and Froneman, 2015), the Kenyan coastline surface waters (110 items/m^3, Kosore *et al*., 2018), the KwaZulu-Natal estuaries in South Africa (754 items/500ml sediments, Naidoo *et al*, 2015), sediments from Bizerte lagoon, Northern Tunisia (3,000-18000 items/kg; Toumi *et al*., 2019), and the African Great Lakes, Lake Victoria (Biginagwa *et al.*, 2016),).

These quantities have been suggested to be affected by various factors including, proximity to urban centers with respect to the human population density, the size of an aquatic ecosystem, and the waste treatment and management systems employed to control the quantity of sewage overflow (Eerkes-Medrano *et al*., 2015). As such, high microplastic quantities have been found in inland aquatic ecosystems that are adjacent to urban centers with high population densities. For instance, in North America the sparsely populated Lakes Huron and Superior recorded an average microplastic concentration of 0.0065 particles/m^2 and 0.013 particles/m^2 respectively (Zbyszewski and Corcoran, 2011). In contrast, the highly populated Lake Erie recorded a pelagic microplastic abundance reaching up to 0.466 particles/m^2 (Eriksen *et al*., 2013). Similarly, the highly populated Bizerte lagoon in Northern Tunisia recorded a benthic microplastic concentration of 6920±395 items/kg dry weight sediment (Toumi *et al*., 2019).

Furthermore, the anthropogenic activities around an aquatic system have been shown to affect the microplastic occurrence and abundance. Industrial activities in Lake Huron's southern parts (Zbyszewski and Corcoran, 2011), and Lake Hovsgol's tourism activities (Free *et al*., 2014) were reported to result in the detection of greater microplastic loads. Lake Naivasha exhibits a growing population around its environs, increasing the activities such as fishing and laundry activities (Musyoka, 2017). The activities have been shown to contribute heavily on microplastic quantities in aquatic systems.

Another factor that influences the microplastic presence and quantities is the water residence time relative to the size of a water body. Lake Hovsgol, a less populated remote lake, recorded a pelagic microplastic count reaching 0.044 particles/m^2 (Free *et al*., 2014). This was discussed to result from the long water residence time experienced and the small size of the lake resulting in high microplastic concentrations. This pattern was further used to explain on the low microplastic densities reported in the larger Lakes Huron and Superior, with respect to the higher microplastic quantities reported in the smaller Lake Geneva (Alencastro, 2012).

A veritable relationship exists between microplastic quantities and the proximity to wastewater treatment facilities. Microplastics recovered near such plants give an indication of peoples' use of certain products such as cleaning products, combined with wastewater treatments that are inefficient in capturing floating microplastics to freshwater bodies (Hoellein *et al*., 2014). For example, higher microplastic concentrations were recovered in a downstream region of a waste water treatment plant as opposed to the upstream region of a north shore channel in Chicago (Hoellein *et al*., 2014). With the increasing informal settlements around Lake Naivasha, household wastewaters have been reported to be discharged into the lake whereas during the heavy rains, inflow rivers Malewa and Karati have been reported to contain sewage-contaminated water from their catchments (Ndungu *et al*., 2015; Ogendi *et al*., 2014). Similarly, the lake receives inflow of contaminated irrigation wastewater from agricultural and horticultural farms (Mutia *et al*., 2012). These factors could negatively impact on the microplastic pollution in the lake.

2.5 Microplastic composition in aquatic environment

Plastic production incorporates a variety of polymers whose composition determines the plastic properties and performances (Andrady and Neal, 2009). These polymers have a great effect on the microplastics durability and buoyancy and eventually affect their environmental fate (Dris *et al*., 2018). The common microplastic polymer types include polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), and polystyrene (PS), among others (Su *et al*., 2016; Yang *et al*., 2015). These blend of low and high density plastic polymers are commonly used as packing materials and thus highly prone to disposal. Besides, they are the most common microplastics reported (Ballent *et al*., 2016; Song *et al*., 2014; Vianello *et al*., 2013).

In Africa, microplastics presence has been confirmed in the South and East African coastal waters, (Kosore *et al*., 2018; Nel and Froneman, 2015), and inland aquatic environs such as the African Great Lakes, South African Kwazu-Natal estuaries and Bizerte lagoon, northern Tunisia (Biginagwa *et al*., 2016; Naidoo *et al*., 2015; Toumi *et al*., 2019). In the African great lakes, PE/PP co-polymer, PE, PES, polyurethane (PU) and silicon rubber polymers were recovered from 20% of the Nile Perch and Tilapia obtained from Lake Victoria. The likely input of these microplastic pollutants was speculated to be the discharge from the urban waste filled drainage ditches into the Mwanza Gulf area (Biginagwa *et al*., 2016).

The shape, color, and size characteristic of microplastics is dependent on their source (Andrady, 2017). Primary sources comprises of all the manufactured plastics in the <5mm size range. This includes manufactured pellets, scrubbers, and other cosmetic products. The manufactured pellets are used in plastic production, scrubbers in cleaning whereas the cosmetic products have a wide spectrum range of usage (Andrady, 2011). Manufactured pellets are common in environments around plastic production enterprises whereas scrubbers and/or micro-beads are mostly found in wastewater discharge sites of industries and households. The primary sourced microplastics find their way into inland aquatic ecosystems through the discharge of household sewage into estuaries and rivers (Fendall and Sewell, 2009).

Secondary sourced microplastics comprises of fragments and fibers, yielded from breakdown and disintegration of larger macroplastics. They originate from consumer products like fishing nets and lines, food packaging items, and synthetic textiles. They may also result from degradable plastic items that are manufactured with the ability to fragment in the environment (Free *et al*., 2014; Hidalgo-Ruz *et al*., 2012). Their breakdown may occur before entering the aquatic ecosystem, such as synthetic fibers from laundry practices, or after as a result of environmental degradation and surface embrittlement (Andrady, 2011).

Secondary microplastics have also been shown to arise as fibers yielded in washing clothes, with the main polymer types recovered being polyester, acrylic, and polyamide. The fibers have been reported to reach up to 100 fibers per liter of washing effluent (Browne *et al*., 2011). Fibers have been recovered in most freshwater ecosystems such as Lake Hovsgol, Mongolia and Lake Garda, Italy. The aforementioned studies suggested on source of these microplastics as the disintegration of larger household plastic items. This suggestion was further supported by the absence of primary pellets and the high quantities of fragments and fibers recovered in the sparsely populated Lakes Garda and Hovsgol (Free *et al*., 2014; Imhof *et al*., 2013).

Secondary sources have been recognized as the major contributor of microplastic pollutants in aquatic environments. They are also associated with sites of high population densities (Duis and Coors, 2016). However, there is incomplete information concerning microplastic sources and composition, relative to their differences in their generation, fragmentation and degradation rates, and distribution drivers (Law and Thompson, 2014). Therefore, with the microplastics' composition in Lake Naivasha still being unknown, assessment becomes necessary, to determine their distribution and potential source of pollution.

2.6 Microplastic distribution in aquatic environments

Properties of the microplastic particles (density, shape, color, and size), combined with the environmental properties determines the particles transport route and dispersal (Ballent *et al*., 2012; Law and Thompson, 2014). In terms of density, most plastics have their densities from 0.85 to 1.41g/cm^3 where polymers such as PP and low and high

density PE exhibit densities that are lower than 1g/cm^3 whereas PS, nylon, and polyvinylchloride (PVC) have higher densities. Low density plastics such as bags, ropes, nettings, high-density food containers and beverage bottles are sources of fragments and fibers (Andrady, 2011). As such, microplastics are widely distributed throughout the water column relative to the diverse range of material densities they result from. Their densities determine whether they occupy a benthic or a pelagic transport route. The less dense microplastics would therefore occupy the surface layers whereas the high density microplastics would be found on the benthos (Ballent *et al*., 2016). However, density modification such as biomass accumulation resulting to biofouling, sedimentation and flocculation processes of microplastics adsorbed on particulate matter can lead to density increase and consequent sinking of microplastics (Andrady, 2011).

Spatially, factors such as anthropogenic activities, wastewater discharge, water velocity, water depth, and seasonal variability influence the microplastic distribution. The microplastic dispersal patterns are driven by large scale factors such as the wind driven surface currents whereas at smaller scales, waves and tides influences the vertical position of microplastic particles (Law and Thompson, 2014). Therefore, the bimodal rainfall pattern experienced in Lake Naivasha, shallow water depth of 6 m, and the high influx from Malewa, Gilgil and Karati Rivers could influence the microplastic abundance and distribution. However, with the contribution of the aforementioned factors known, the microplastic load in Lake Naivasha is still unknown.

2.7 Microplastic analysis methods
Due to non-uniform sizes of microplastics, studies have reported different classification (Tagg *et al*., 2015) in both freshwater and marine microplastics studies. This is due to varied differences in methodologies used to isolate them and the different metrics used to quantify them (Andrady, 2017). Techniques for sampling microplastics, such as the selective and volume-reduced methods, have been used with differing collection, identification and enumeration methods. Selective sampling has been employed to quantify microplastics in sediments whereas water parcels and other sediments studies have used volume-reduced sampling successfully (Li *et al*., 2018). However, due to restrictions by sampling methods, only 0.3 mm size-scale microplastics are assessed in

trawl collected neustonic samples, with smaller particles being examined for sediment and biota samples (Qiu *et al*., 2016).

In the laboratory, microplastic analysis comprises of two steps. First, the microplastic samples are taken through an extraction and purification step. This simply involves the separation of microplastics from their initial matrix with the aim of simplifying and improving the subsequent identification and quantification processes. The most often employed method for separation is density separation. It involves agitating a sample in a liquid of known density to allow for the floatation of lower density particles. This simplifies the recovery of the less dense microplastics from the supernatant by filtration (Qiu *et al*., 2016). Elutriation and floatation are as such, density separation techniques that have successfully been used to recover microplastics especially in sediments (Imhof *et al.*, 2013). However, density separation by sodium chloride (NaCl) method has been the most reliable and common method of separation from both surface waters and sediments. This method has also been reported to be appropriate for regular monitoring of environmental policies since it is simple, fast and doesn't employ hazardous chemicals (Free *et al*., 2014).

The purification process can be achieved through either chemical or enzymatic degradation to remove the interfering organics such as tissues. Different mechanical degradation approaches have been adapted that involve treatment of the microplastic samples with varying chemicals. Such chemicals include; 10-30% v/v hydrogen peroxide (H_2O_2), mixtures of H_2O_2 and mineral acids like H_2SO_4, and non-oxidizing acids such as hydrochloric acid (Cole *et al*., 2014). The strong oxidizing agents such as sulphuric and nitric acids have been reported to destroy the microplastics whereas the non-oxidizing acids are required in high concentrations and yield a lot of organic post-digestion residues (Li *et al*., 2018). Enzymatic degradation involves the incubation of microplastic samples with a combination of technical enzymes like amylase, cellulose, chitinase, lipase, or proteinase, that specifically remove proteins, carbohydrates, and lipids (Cole *et al*., 2014). However, this method is unpopular as it is still under optimization whereas the biological enzymes are costly (Li *et al*., 2018). Therefore,

since the H_2O_2 based method impacts negligible damage to microplastics, it has become the most popular and thus used in this study for sample digestion.

The second step in microplastic analysis involves the identification and quantification of the recovered microplastics. The microplastic samples are normally subjected to visual sorting, mainly under a microscope, to count and collect microplastics that are subject to further spectroscopic analysis (Qiu *et al*., 2015). However, despite being used by a majority of studies, visual sorting does not provide reliable and/or accurate results on the microplastic quantities due to the adsorption of environmental matter such as algae and/or clay, especially for non-pre-treated samples. These limitations highlight the need for further approaches such as spectroscopic techniques to improve the reliability of plastic particles identification (Song *et al*., 2015).

The main spectroscopic techniques that have been used in microplastics analysis are FT-IR, Raman spectroscopy, and scanning electron spectroscopy (Qiu *et al*., 2016). This study employs the use of FT-IR spectroscopy to determine the composition of microplastic particles. Testing involves excitation of the microplastic samples to induce structure-specific vibrations that can be detected. That is, on sample irradiation with infrared light of a defined wavelength range, a characteristic spectrum is produced in the fingerprint range that allows for identification of the nature of the polymer, specifically obtained through spectra comparison with that of a standard reference material in the equipments database (Song *et al*., 2015). The methods working principle is the change in the permanent dipole moment of a chemical bond, therefore being efficient for the determination of molecules that possess polar functional groups like carbonyl.

In attenuated total reflectance (ATR) mode, FT-IR is preferred as it requires minimal or no sample preparation even for the thick and opaque microplastic samples. Besides, this mode produces stable spectra even from the irregularly shaped microplastic surfaces (Smith, 2011). This method is also cost effective and has been successfully employed in most studies for microplastics analysis (Qiu *et al*., 2016).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study area

Lake Naivasha is a freshwater lake in Kenya and is part of the Great Rift Valley. The lake is located in the Kenyan Rift Valley at 1,890 m (6,181 ft.), about 80 km northwest of Nairobi at the rain shadows of the Aberdare ranges. The lake covers an average water surface area of 139 km^2 with a mean and maximum depth of 6 m and 30 m respectively. It is fed by the perennial river Malewa (80% of freshwater inflow), from the Nyandarua and Kinangop mountain ranges as the main catchment areas, and the rest supplied by the Gilgil and Karati rivers (Mutia *et al*., 2012).

The sampling points were purposely selected as shown in Figure 1, based on the possible microplastic entry routes into the lake.
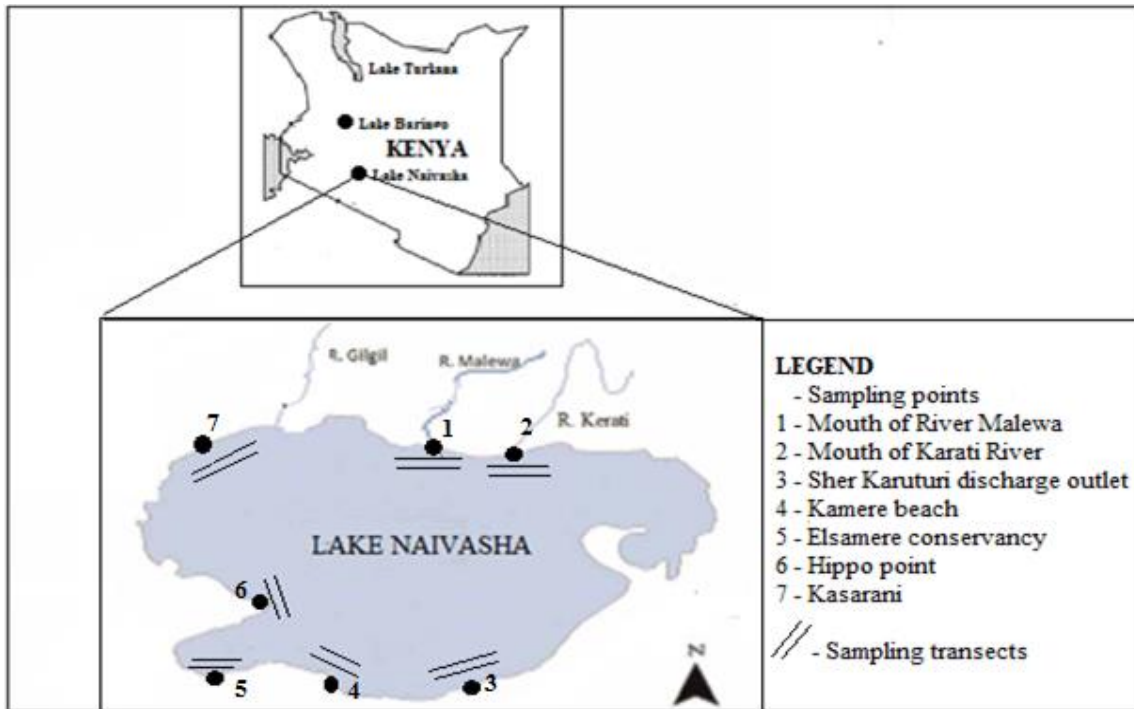

Figure 1: Map of Lake Naivasha showing the seven sampling points.
Adopted from Omondi *et al*., (2015).

Mouths of Malewa and Karati rivers were assessed to represent the contribution and possible contamination by the upstream natural processes and anthropogenic activities in the catchments (Mutia *et al.*, 2012). Kasarani and Sher Karuturi represented discharge outlets (Mutia *et al*., 2012) from the floriculture farms whereas Kamere beach was assessed to represent tourism activities and other human disturbances such as laundry and fish landing in the lake (Musyoka, 2017). Hippo point was used to represent areas of minimal anthropogenic activities (Mutia *et al*., 2012) whereas the Elsamere conservation center was assessed to represent an area protected from human activities (Musyoka, 2017).

3.2 Sampling

The study was laid out as a Randomized complete block design (RCBD) in the seven designated sampling sites. Sampling was done in January 2019, where a total of 21 trawls were conducted (average of three trawls per site) to collect pelagic debris in the shorelines of the selected locations of the lake. Trawls were collected using a zooplankton net (diameter: 0.3m, mesh size: 150 microns, net length: 1.2 m) fitted with a detachable PVC cod end with a nitex nylon lining. Trawling was conducted with an average tow speed range of 2.5- 3.5 knots. The residues were thoroughly rinsed with the lake water into glass bottles and transported to the lab at 4℃. Similarly, a total of 21 sediment samples (3 replicate samples for each) were collected from the seven study locations (Table 1) using an Ekman grab sampler along the sampling transects and transported to the lab in aluminum foil covered plastic containers. Measurement of physical chemical parameters (temperature, pH, TDS, DO, turbidity, salinity and electrical conductivity) of surface waters at each sampling location was done *in situ* using a Professional Plus (fitted with Quatro Multi-parameter Cable) water quality instrument. Water samples were taken with plastic bottles, pretreated with 0.1M sulphuric acid, and transported to the University of Embu laboratory at 4℃ where the nutrient levels (total nitrogen and total phosphorus) were determined.

Table 1: A summary of specific coordinates and depth of the locations sampled for physical chemical parameters and surface sediments

Sampling location	Geographical location	Station number	Latitude	Longitude	Depth (m)
River Malewa mouth	North	1	-0.71512S	36.35023E	2.1
		2	-0.71347S	36.34921E	2.1
		3	-0.71361S	36.34809E	2.3
River Karati mouth	North	1	-0.72411S	36.39158E	1.7
		2	-0.72462S	36.39142E	2.1
		3	-0.72427S	36.39059E	2.0
Sher Karuturi discharge outlet	South	1	-0.82919S	36.35652E	2.1
		2	-0.82777S	36.35742E	2.9
		3	-0.82617S	36.36007E	2.2
Kamere beach	South	1	-0.81485S	36.32453E	2.0
		2	-0.81358S	36.32467E	4.7
		3	-0.81538S	36.32744E	1.1
Elsamere Conservation Centre	South west	1	-0.81253S	36.31423E	4.9
		2	-0.81333S	36.31319E	4.3
		3	-0.81283S	36.31308E	5.4
Hippo point	West	1	-0.78734S	36.31328E	2.0
		2	-0.78792S	36.31628E	3.8
		3	-0.79036S	36.31598E	5.2
Kasarani	North west	1	-0.71787S	36.31591E	3.0
		2	-0.71835S	36.31459E	3.3
		3	-0.72144S	36.30825E	4.3

3.3 Nutrient analysis

Total phosphorus (TP) was analyzed using the molybdenum blue-ascorbic acid method (Yan *et al*., 2016). It involved mixing 25 ml of the sample with 4 ml of a combined reagent (5N H_2SO_4, Potassium antimonyl tartarate, 4% ammonium molybdate and ascorbic acid in the ratio 10:1:3:6 respectively), shaken well and left to stand for 10-20 minutes. The absorbance was then recorded in a SPECTRO V-11D MRC UV spectrophotometer at 880 nm. The TP concentrations were determined using a standard KH_2PO_4 calibration curve.

Total nitrogen (TN) was determined using the modified Kjeldahl method (Yan *et al*., 2016). The method involved diluting 10 ml of the sample with 250 ml distilled water. This was followed by addition of 50 ml of the digestion reagent (134 g K_2SO_4 and 7.3 g $CuSO_4$ dissolved in 5N H_2SO_4) to break and convert all the nitrogen bonds into ammonia

(NH_4^+) ion. The solution was then passed through a steam distillation system where the NH_4^+ ions were converted into ammonia using 50 ml of a sodium hydroxide- sodium thiosulfate reagent (500 g NaOH and 25 g $Na_2S_2O_3.5H_2O$ dissolved and diluted with distilled water to 1 L). The distillation was carried out using 50 ml of 0.04N H_2SO_4 as the absorbing solution and until an approximate 200 ml distillate was collected. The distillate was diluted to 300 ml using distilled water and the nitrogen quantity determined colorimetrically.

3.4 Microplastics extraction

The collected surface water trawls were placed in 500 ml beakers and oxidized with 30% H_2O_2, catalyzed by 0.05M Fe (II) solution with hot plate heating (to a maximum of 75 ℃) to degrade and decompose organic matter (Masura *et al.*, 2015). The beaker components were cooled and filtered through a Whatmann filter paper (pore size 1 μm) with the walls of the filtering device washed multiple times with pre-filtered de-ionized water. The filters were transferred into clean petri dishes, covered and oven-dried (DHG-9053 blast drying oven) at 50 ℃ for 24 hrs and stored in a contamination free area awaiting microscopic examination.

For sediments, triplicate 50 g samples were investigated for each site using modified Masura *et al.*, (2015) method. The sediments were oven-dried at 70℃ to a constant weight and sieved through a 5 mm sieve. In a 500 ml beaker, the sieved dry sediments were mixed with 50 ml of 0.05M Fe (II) solution and 100 ml of 30% v/v H_2O_2 to catalyze the decomposition of biogenic organic matter. The beaker contents were heated to a maximum of 75℃ with cooling to subside boiling. The samples were again oven-dried at 70℃ to achieve a constant weight. To the beaker contents, 200 ml saturated NaCl (1.2 g/cm^3) was added and thoroughly stirred for 2 mins. The beaker was covered and left overnight to settle. The supernatant was poured through a Whatmann filter paper (pre-dried at 50℃) and rinsed three times with distilled water. The filter paper and its components were dried for 24 hrs and then stored in clean petri dishes awaiting microscopic analysis.

3.5 Microplastic identification

Dried filter papers were carefully examined under a JAPSON HG 671572 dissecting microscope (up to ×40 magnifications) where counting and categorization (by shape and color) was done as per Hidalgo-Ruz *et al.*, (2012) and Masura *et al*., (2015) selection and identification rules. Under the ×40 magnification scope, MP particles with a 5mm diameter field of view or less were identified while the rest were discarded as macroplastics. Rules followed for identification of microplastics included; particles that could not be torn apart by tweezers, particles having distinguishable and uniform colors all through, particles without visible cellular or organic structures such as knots and particles that were equally thick throughout their length.

Thus, in this stage, the microplastic particles were quantified (abundance), and also analyzed for their physical characteristics that included color and shapes. Each particle was recorded against its visual observed color and also on its shape. The shape categories were classified into fibers/filaments, fragments, films and pellets as per Hidalgo-Ruz *et al.*, (2012).

3.6 FT-IR spectroscopy

Identified particles were counted and randomly selected for FT-IR analysis using IRAffinity-1S FT-IR (SHIMADZU EUROPA). The FT-IR analysis was conducted in attenuated total reflectance mode where spectra wavelength ranging 500-4000 cm^{-1} was taken in a 1 minute accumulation time and 0.5 cm^{-1} spectral resolution. Spectral match was done with LabSolutions IR spectral library. The spectral analysis followed the method of Yang *et al*. (2015) where only spectral matches with a quality index of ≥0.7 were accepted. To account for airborne contamination, sample-free air controls were run between MP samples. No MPs were found in the control analysis hence negligible working contamination.

3.7 Contamination control

All equipments used were pre-rinsed thoroughly using distilled water before use. Similarly, plastic equipments were replaced with non-plastics where possible, and where not, thorough rinsing with distilled water was done followed by inspection under a microscope to ensure no plastic fragments were present or generated.

Cotton lab coats were worn at all times during sample handling to keep the process sterile. Samples were always covered with aluminum foil during processing. A single person handled all samples while all the working reagents were pre-filtered through a Whatmann filter paper (pore size 1 μm).

Procedural blanks were set to monitor environmental and handling contamination during sample processing. This was done by treatment of 1L pre-filtered working distilled water with H_2O_2 followed by filtration. In a total of three blank setups, an average of 0.33±0.587 particles was found under a microscope. Hence, processing contamination was minimal and thus negligible.

3.8 Data analysis

The mean differences in microplastic concentration and composition among the several study sites were determined using one-way analysis of variance (ANOVA) at a <0.05 significance level. Mean separations in microplastics abundance was done using Tukey's Honestly Significance Difference (HSD) test whereas that of physical chemical parameters was done using Least Significance Difference (LSD). All statistical data analysis was done using SAS® software (SAS 8.2). Bar graphs were drawn using Microsoft Excel 2010.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Physical chemical parameters

The physical chemical parameters considered in this study were pH, temperature, conductivity, salinity, turbidity, total dissolved solids (TDS), dissolved oxygen (DO), total nitrogen (TN), and total phosphorus (TP). These were measured *in situ* and the results presented in Table 2 and 3.

The mean temperature showed significant differences between the sampling sites with Elsamere conservancy being the warmest (26.4 ℃) and the mouth of Karati River recording the lowest temperature (21.0 ℃) as presented in Table 2. The temperature recorded at Elsamere conservancy was statistically similar to that recorded at Kamere beach, with similar observations being made for Hippo point, Kasarani, and Karuturi sampling sites. The higher temperature at Elsamere conservancy and Kamere beach was attributed to the relatively low water volumes and thus the water took a shorter period to warm up (Ndungu *et al*., 2015). Similarly, the lower mean water temperature recorded at the mouths of Malewa and Karati rivers would be attributed to result from the large water inflows causing the dilution effect. Further, their shores were highly infested by macrophytes and hyacinth growth that formed a cover, blocking the exchange of heat between the water column and the atmosphere.

Being a freshwater lake, Lake Naivashas' mean pH was mildly alkaline with the mean values recorded being statistically different between the sampled sites (Table 2). The highest pH was recorded at Elsamere conservancy (7.92) whereas the least was recorded at Karuturi discharge outlet (7.25). The pH recorded at Elsamere conservancy was found to be statistically similar with that at Kamere beach, with similar observations being made for Kasarani, and mouths of Malewa and Karati Rivers. The mild alkalinity could be attributed to volcanic origin of the lake (Ndungu *et al*., 2015). Lake Naivasha was also found to have salinity mean values ranging between 0.13 and 0.14 ppt with Hippo point, mouth of Malewa River, Kamere beach, Kasarani and Karuturi sites being shown to have statistically similar salinity levels. The low pH and salinity levels in Lake Naivasha have been attributed to high freshwater influx from the Malewa, Gilgil, and

Karati Rivers. These rivers drain from the Aberdares Range and Kinangop catchments where high amounts of precipitation are experienced (Ndungu *et al*., 2015).

The turbidity mean values recorded in Lake Naivasha exhibited significant differences between the sampled locations (Table 2). The highest turbidity levels were recorded at the mouth of Malewa River (47.68 NTU) whereas the least was recorded at Hippo point (12.44 NTU). The mouth of Karati River, Kamere beach, and Kasarani sites were found to have statistically similar turbidity levels, with similar observations being made for Elsamere conservancy and Hippo point sites. The relatively higher turbidity levels recorded at the mouth of Malewa River was attributed to the increased settlements and urbanizations in the lakes' catchments, and the large water abstractions for agriculture and domestic uses. Further, the levels recorded at the mouth of Karati River, Kamere beach, and Kasarani could be attributed to the increased anthropogenic activities around the lake, together with other natural mechanisms such as eutrophication (Mironga *et al*., 2012). The higher water transparency recorded at Hippo point and Elsamere conservancy was attributed to the minimal human activities at these sites (Njiru *et al.*, 2015).

The mean dissolved oxygen (DO) values recorded showed significant differences between the sampled locations of Lake Naivasha. The highest mean DO levels was recorded in Sher Karuturi (9.0367 mg/L) and Kamere beach (8.4567 mg/L) whereas Mouth of Karati River recorded the lowest mean DO concentrations (6.8867 mg/L) as shown in Table 2. The mouths of Karati and Malewa Rivers, and Kasarani sites were found to have significant similar DO levels. They recorded relatively lower DO levels that were attributed to the effect of water hyacinth infestation, the metabolic activities of the epiphytic organisms in the lake, and the discharge of pollutants by the surrounding flower farms and industries (Mironga *et al*., 2012). Besides, low/reduced dissolved oxygen has been related to environmental tragedies such as the death of over 1000 fish that was experienced in February 2010, raising concerns on the continued deterioration of Lake Naivashas' health (Njiru *et al.*, 2015).

Table 2: Physical chemical parameters of surface waters in Lake Naivasha

	ML	EL	HP	KT	KMR	KSR	KRTR
Temp (^{0}C)							
Mean ± S.D.	22.90±0.30[c]	**26.43±0.32[a]**	23.90±0.53[b]	21.00±0.90[d]	**25.77±0.47[a]**	23.97±0.64[b]	23.97±0.16[b]
pH							
Mean ± S.D.	7.34±0.08[c,d]	**7.92±0.03[a]**	7.62±0.12[b]	7.44±0.05[c]	7.82±0.09[a]	7.37±0.06[c,d]	7.25±0.06[d]
Sal (ppt)							
Mean ± S.D.	0.13[b]	0.13±0.06[a,b]	0.13[b]	0.14±0.01[a]	0.13[b]	0.13[b]	0.13[b]
Turbidity(NTU)							
Mean ± S.D.	**47.68±1.96[a]**	15.13±1.08[d]	12.44±3.03[d]	29.46±1.60[b]	25.87±4.62[b,c]	27.92±0.52[b]	22.84±2.41[c]
DO(mg/L)							
Mean ± S.D.	7.04±0.29[d]	8.23±0.04[b,c]	7.99±0.08[c]	6.89±0.24[d]	8.46±0.29[b]	6.70±0.37[d]	**9.04±0.11[a]**
Cond (mScm^{-1})							
Mean ± S.D.	0.260±0.003[e]	0.276±0.004[a,b]	0.277±0.002[a]	0.263±0.002[e]	**0.278±0.002[a]**	0.268±0.002[d]	0.270±0.002[c,d]
TDS (ppm)							
Mean ± S.D.	0.1786±0.0005[c]	0.1792±0.0003[b,c]	0.1790±0.0004[b,c]	**0.1845±0.0007[a]**	0.1795±0.0002[b]	0.1794±0.0007[b]	0.1792±0.0003[b,c]

*The different superscript letters within a row indicate sampled locations with mean significant differences in the physical chemical parameter at $p < 0.05$ (n=3). Sites with similar letters indicate no significant differences. S.D. = Standard Deviation. ML- Mouth of River Malewa; KT- Mouth of Karati River; KSR- Kasarani; KRTR- Sher Karuturi discharge outlet; KMR; Kamere beach; EL; Elsamere conservancy; HP- Hippo point.

The mean conductivity levels recorded in Lake Naivasha were found to be statistically different between the sampled locations (Table 2). The highest mean conductivity was recorded at Kamere beach (0.278 mScm^{-1}) whereas the least was recorded at the mouth of Malewa River (0.26 mScm^{-1}). Hippo point and Kamere beach sites were found to have statistically similar conductivity levels, with similar observations for the mouths of Karati and Malewa Rivers. Lake Naivashas' volcanic origin has been associated with the increased concentrations of dissolved minerals (Ndungu et al., 2015), which greatly influences conductivity. Pollution as a result of waste discharge into the lake from the informal settlements of Kamere beach could also be attributed to the high conductivity means recorded. Being a direct measure of carbonate salts, which accounts for up to 80% of conductivity in aquatic systems, the range of conductivity in Lake Naivasha was 0.260-0.278 mScm^{-1}. Thus, the carbonate salts concentration in this lake was lower, relative to neighboring lakes in the Great Rift valley such as Lake Baringo, Lake Bogoria, Lake Nakuru and Lake Elementaita whose conductivities have been reported to span in the range of 0.963-65 mScm^{-1} (Ochieng et al., 2007).

The total dissolved solids (TDS) levels recorded in Lake Naivasha were also found to be statistically different between the sampled locations. The highest mean TDS value was recorded at the mouth of Karati River (0.1845 ppm) and the lowest recorded at the mouth of Malewa River (0.1786 ppm). Statistically similar TDS values were found at Kamere beach and Kasarani sites (Table 2), and also at Hippo point, Elsamere conservancy and Karuturi sites. Lake Naivasha, however, has low levels of dissolved solids compared to other lakes in the East African rift system. These has been reported by researchers to result partly from the qualitative importance of water inflow, outflow, and human activities, such as agriculture around the lake (Njiru et al., 2015).

The total nitrogen (TN) levels recorded in Lake Naivasha were found to be statistically different between the sampled locations (Table 3). The highest TN levels were recorded in the mouth of Malewa River (0.68 mg/L) while the lowest was recorded at Hippo point (0.25 mg/L). The mouth of Karati River was found to have statistically similar TN value with Kamere beach. Similar observations were made for the Total phosphorus (TP) quantities in the sampled locations of Lake Naivasha (Table 3). The highest TP value

was recorded in the Mouth of Malewa River (0.086 mg/L) and the least at Hippo point (0.042 mg/L). Besides contribution to water levels in Lake Naivasha, river discharge is also known to contain organic matter and sediments that comprises of nutrients and particles (Ndungu *et al*., 2015). These organic matters decompose to yield phosphorus that is released into the water column, which in excess, together with total nitrogen leads to the rapid growth of algal blooms. This has been reported to compromise the availability of dissolved oxygen whereas decreasing the water transparency, a limiting factor for aquatic organisms that are dependent on vision for prey identification (Ndungu *et al*., 2015). Thus, the high levels of these nutrients reported in the lakes' major inflow river Malewa triggers concerns on the contribution of these rivers, from activities in the catchments such as agriculture, on the lakes pollution.

Moreover, with increased population around the lake and its catchments, there is increased pressure on the waste disposal facilities, land and the soil fertility. These results in forest clearance and the inevitable use of pesticides and fertilizers by both the small-scale farmers and the large-scale horticultural farms (Njiru *et al*., 2017). These activities increase the nutrient levels which are transported into Lake Naivasha through the inflow-rivers and especially during the heavy rains.

Table 3: Surface waters nutrient levels.

	ML	EL	HP	KT	KMR	KSR	KRTR
Total nitrogen(mg/L) Mean ± S.D.	0.68 ± 0.01^a	0.43 ± 0.01^c	0.25 ± 0.02^e	0.37 ± 0.03^d	0.38 ± 0.02^d	0.49 ± 0.02^b	0.44 ± 0.02^c
Total phosphorus (mg/L) Mean ± S.D.	0.086 ± 0.002^a	0.050 ± 0.004^c	0.042 ± 0.002^d	0.057 ± 0.003^b	0.057 ± 0.002^b	0.047 ± 0.002^c	0.051 ± 0.003^c

The different superscript letters indicate sampled locations with mean significant differences in the nutrient levels at $p < 0.05$ (n=3). Sites with similar letters indicate no significant differences.

ML- Mouth of River Malewa; KT- Mouth of Karati River; KSR- Kasarani; KRTR- Sher Karuturi discharge outlet; KMR; Kamere beach; EL; Elsamere conservancy; HP- Hippo point.

S.D. – Standard Deviation.

4.2 Microplastic abundance

Microplastic particles were recovered in all the studied locations surface waters and sediments, with classification being done quantitatively and qualitatively. In surface waters, microplastics ranged between 0.18 ± 0.016 and 0.63 ± 0.067 particles/m^2 (Figure 2). The mean pelagic microplastic concentration in Lake Naivasha was determined to be 0.407 ± 0.135 particles/m^2 measured over 21 shoreline trawls. A significant difference ($p<0.05$) in mean microplastics concentrations was observed in the studied locations, greatest mean concentrations being recorded in the Mouth of Malewa River (0.633 particles/m^2).
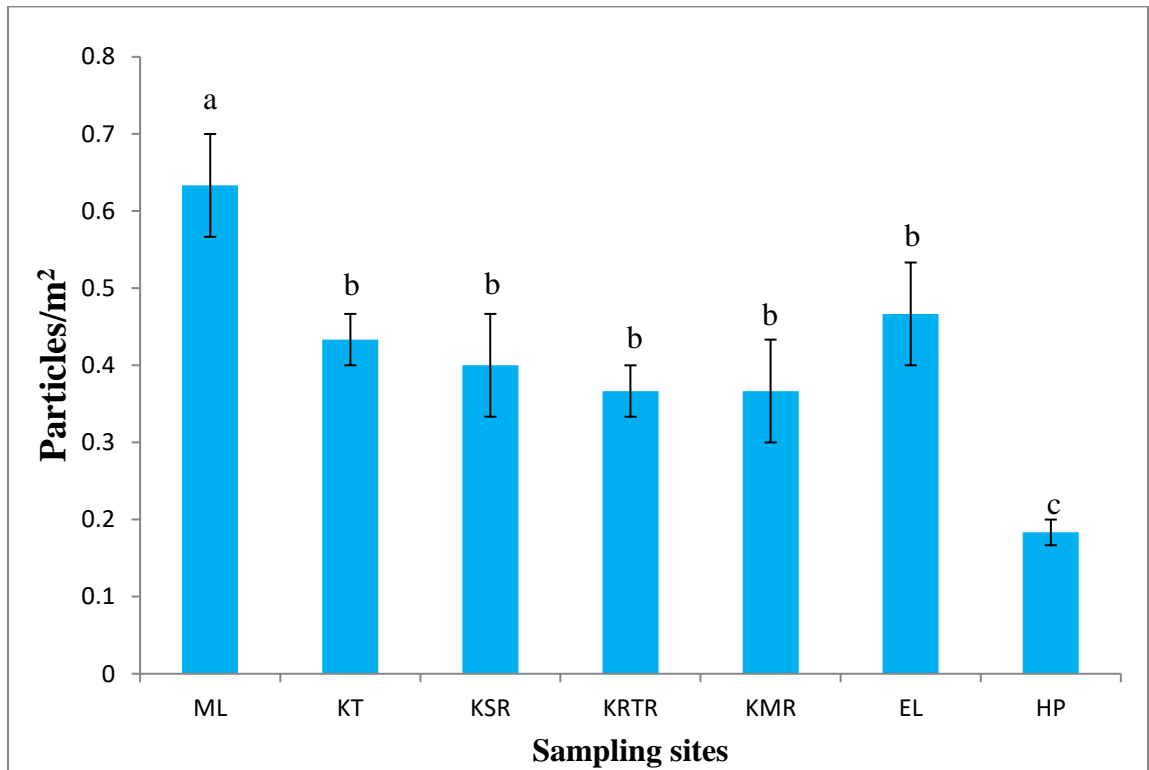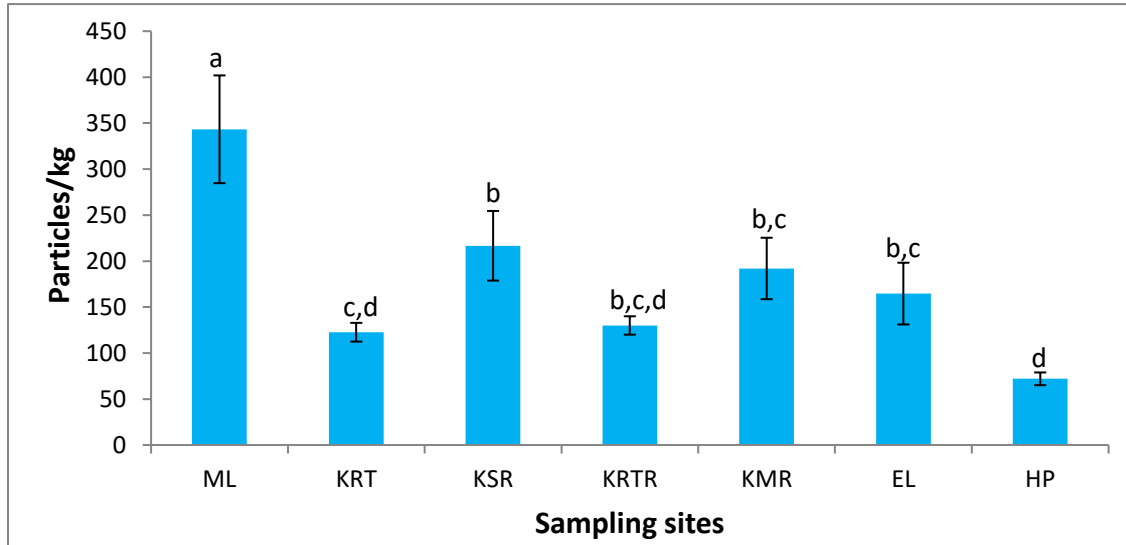

Figure 2: Microplastics abundance in the shoreline surface waters of the seven studied locations of Lake Naivasha

ML- River Malewa mouth; KT- Karati River mouth; KSR- Kasarani; KRTR- Sher Karuturi discharge outlet; KMR;Kamere beach; EL; Elsamere conservancy; HP- Hippo point.

The different letters above the bars indicate sampled locations with mean significant differences in microplastic concentrations at $p < 0.05$. Sites with similar letters indicate no significant differences. The error bars represent the standard deviation of the microplastic means at each sampling site.

31

Similarly, microplastics recovered from the sediment samples ranged between 72±6.9 and 343.3±58.6 particles/kg dry weight (d.w) sediment. The average microplastic load in Lake Naivashas' surface sediments was determined to be 177.3±87.4 particles/kg d.w sediment. A comparable trend in the spatial distribution of microplastics to that of surface waters was evident, highest and low mean concentrations also being recorded in the mouth of River Malewa and Hippo Point, respectively (Figure 3).

Figure 3: Microplastics abundance in the shoreline surface sediments of the seven studied locations of Lake Naivasha.

ML- River Malewa mouth; KRT- Karati River mouth; KSR- Kasarani; KRTR- Sher Karuturi discharge outlet; KMR;Kamere beach; EL; Elsamere conservancy; HP- Hippo point.
The different letters above the bars indicate sampled locations with mean significant differences in microplastic concentrations at $p < 0.05$. Sites with similar letters indicate no significant differences. The error bars represent the standard deviation of the microplastic means at each sampling site.

The high spatial heterogeneity and variability in microplastics abundance exhibited in Lake Naivashas surface waters and sediments could be attributed to result from a myriad of factors, including but not limited to the plastic properties, meteorological and hydrodynamic conditions and river-line input. The plastic properties affect microplastic distribution in aquatic systems due to the diverse range of material densities they result from. These densities would thus determine whether the microplastics are recovered

32

from the surface waters or sediments (Ballent *et al*., 2016). On the other hand, the climatic conditions influences the presence of local wind patterns that are responsible for the general water circulation (Zhao *et al*., 2016).

Higher microplastic concentrations were detected at the mouth of River Malewa, an area dominated by large water inflows, approximately 80-90% of Lake Naivasha waters. River Malewa is a long channeling river from the Kinangop catchments. Its' channel is marked by increased agricultural activities, population growth and urbanization (Mutia *et al*., 2012; Ndungu *et al*., 2015). Post-hoc HSD Tukey's test showed the abundance of microplastics in this location was significantly high ($p<0.05$) from all the other sampled locations. This could be as a result of microplastic contamination by upstream natural processes, anthropogenic activities such as industrial and domestic waste, and the run-off from sewage–sludge based fertilizer used on farmlands in its catchments (Faure *et al*., 2015; Mutia *et al*., 2012). Moreover, the high concentration of microplastics in the Mouth of River Malewa gives a clear indication on the relative importance of microplastics input, through tributaries and rivers from terrestrial environments, into inland aquatic ecosystems and consequently into oceans.

Similarly, most of the studied locations showed high microplastic abundances that could be attributed to adjacency to informal settlements (Kamere), adjacent horticultural and agricultural activities (Kasarani), and fishing and tourism activities (Kamere, Karuturi, Mouths of Malewa and Karati Rivers). Moreover, Elsamere Conservancy and Hippo Point, which are protected areas with minimal anthropogenic activities, also recorded high MP abundance. Thus, considering that the pelagic MP density presented a relatively even distribution over the entire Lake Naivasha shoreline surface waters, the general MP distribution could be attributed to the general water circulation by action of wind and waves as illustrated by Nel and Froneman (2015).

Lake Naivasha surface waters exhibited a relatively high abundance of microplastics as compared to most inland freshwaters studied such as Lake Hovsgol in Mongolia Asia (0.02 particles/m^2), Lake Michigan in USA (0.017 particles/m^2), Lake Geneva in Europe (0.048 particles/m^2), and the Laurentian Great Lakes in Europe (0.043 particles/m^2). For instance, Lake Hovsgol is a remote mountain lake that showed decreased MP density with increased distance from its southwestern shore. In addition, the high MP quantities

Table 4: Reports of freshwater lakes microplastic abundance

Studied area	Collection	Collection Cut-off size (μm)	Abundance (particles/m^2)	Main type recovered	Reference
Lake Naivasha (range) mean$\pm$std. dev.	Plankton net	150	0.23-0.7 0.407±0.135	Fiber (81%)	This study
Lake Erie (range)	Manta net	333	0.004-4.667	Fragments	Eriksen *et al*., 2013
Lake Geneva (mean)	Manta net	300	0.22 ± 0.16	Fragments	Faure *et al*., (2015)
Lake Maggiore (mean)	Manta net	300	0.220 ± 0.150	Fiber	Faure *et al*., (2015)
Lake Taihu (range)	Plankton net	333	0.01-6.8	Fibers (70%)	Su *et al.*, (2016)
Three Gorges Dam China. (mean)	Plankton net	112	8.47		Zhang *et al*. (2015)

(reaching up to 0.044 particles/m^2) reported were attributed to its small size and the long water residence times (Free *et al*., 2014). A comparison of the levels of abundance of microplastics in Lake Naivasha with other lakes is presented in Table 4.

The high microplastics abundance detected in Lake Naivasha was attributed to several factors. First, the anthropogenic activities around the lake such as fishing and tourism could impact in high microplastic counts. Macro-plastic litter was evident in all the studied shores and comprised of soft-drink cans, plastic bags, plastic water cans among others. Discarded fish nets and lines that could decompose to yield microplastics (Horton *et al*., 2017) were also present in most shorelines and surface waters near shore. Similarly, microplastics present in sediments were mainly resulted from sinking of dense plastic polymers such as PET and PVC. They could also to a less extent be brought about by biofouling of less dense plastic polymers (Tsang *et al*., 2017). Being long-term sink for microplastics, sediment samples gives a reflection of the long-term water and land interfaces interaction and can be used to inform on the fate of these pollutants (Wagner *et al*., 2014). Therefore, microplastics in Lake Naivasha sediments could source from recreational, tourism, and fishing activities.

Secondly, the lake is small (surface area approximately 139 km^2), shallow (mean depth of 6 m), and highly susceptible to considerable water fluctuations in the long, dry and hot periods that increase the evaporation rates. Moreover, Lake Naivasha has no visible outlet and outflows through ground water seepage and water abstractions (Ndungu *et al*., 2015). Thus, the lake is prone to experience concentration effect, similar to relative small Lake Geneva which recorded a high microplastic abundance than the larger Lakes Huron and Superior (Faure *et al*., 2015).

Thirdly, sampling time relative to the wind speed is a considerable factor with respect to microplastic abundance in surface waters. The absence of wind has been reported to contribute to unlike concentrations as a result of vertical mixing and re-suspension of benthic microplastics (Frère *et al*., 2017; Maes *et al*., 2017). This would in turn favor surface stratification (Kosore *et al*., 2018) leading to microplastics accumulation in the surface waters. The use of plankton nets instead of the dedicated surface/neuston nets has also been reported to result in the recovery of higher microplastic concentrations (Su *et*

al., 2016; Wang *et al.*, 2017). For example, in Siene River France, where two non-identical mesh sizes were used to sample surface water microplastic particles, an 80 μm mesh-size net yielded microplastic concentrations varying between 3-106 particles/m^3 whereas the 330 μm mesh-size manta trawl net yielded concentrations of 0.28-0.45 particles/m^3. Moreover, with the abundant recovered microplastics being fibers, the former recorded 52% of the plastic fibers being smaller than 1000 μm while the latter recorded only 25% (Dris *et al*., 2015). Thus, considering that for the present study sampling was conducted during the morning hours and the wind speed was relatively low, this together with the smaller sized sampling net mesh (150 μm) employed, could have increased microplastics concentration in magnitude several orders higher than those collected in windy conditions and using the common 300 µm mesh size sampling net.

In Kasarani sampling location, water barriers were evident that were comprised of soil/sand-packed sacks arranged on the shores and covered with a plastic bag. This was used to prevent the action of waves and encroachment of the lake into nearby farms and settlements. As much as erosion is reduced, the action of wind and wave energy could result in the degradation and fragmentation of the plastic cover resulting in the generation of microplastics (Andrady, 2011), present in Lake Naivasha surface waters and sediments.

4.3 Microplastic compositions

4.3.1 Physical characteristics

Microplastics recovered were sorted into four main shape categories, (fibers/filaments, fragments, films and pellets). Microplastic fibers and fragments were present in all the samples from all locations. Films were present in five out of the seven studied locations in surface waters (Figure 4). Pellets were not present in all the samples, corroborating Faure *et al*., (2015) study that reported on pellets presence in beach sediments and not in surface water columns or inshore sediments.
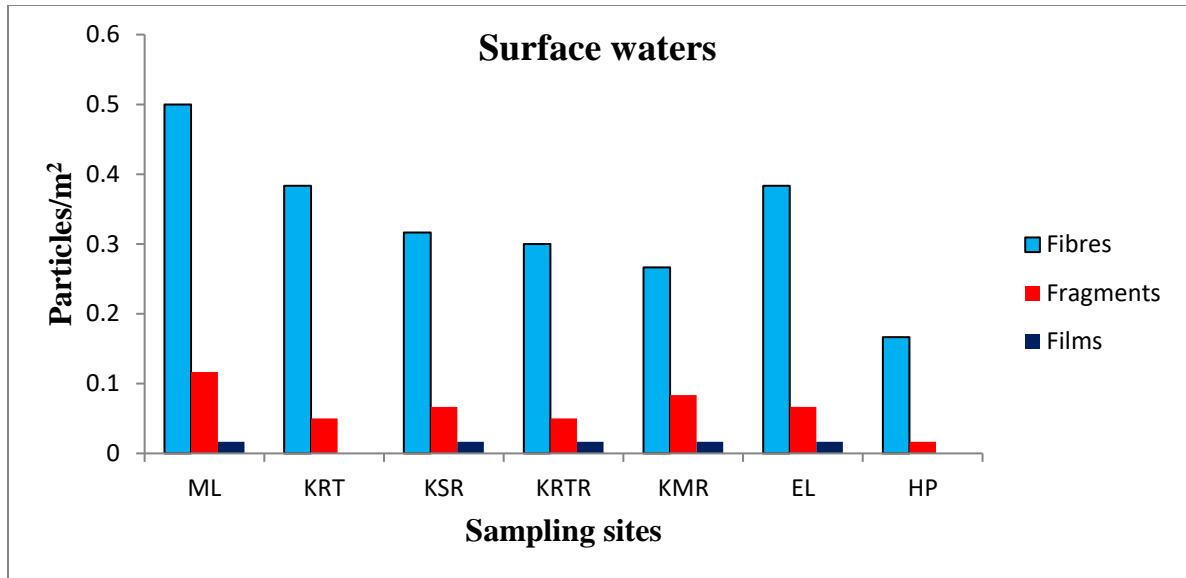
Figure 4: Proportions of shape categories of the microplastics recovered from Lake Naivasha surface waters.

ML- River Malewa mouth; KRT- Karati River mouth; KSR- Kasarani; KRTR- Sher Karuturi discharge outlet; KMR;Kamere beach; EL; Elsamere conservancy; HP- Hippo point.

In surface waters, fibers/filaments showed a dominating occurrence (n=69.5 ≅81%), and a significant difference (p<0.05) in concentration between the studied locations of Lake Naivasha. On the other hand, fragments (n=13.5) and films (n=2.5) did not show any significant differences in the studied locations of the lake. The dominance of fibers/filaments in surface waters matches with studies in Europe (Faure *et al*., 2015), Asia (Su *et al*., 2016), and Kenyan marine coastline which recorded 76% fibers/filaments (Kosore *et al*., 2018). As such this study corroborates with Dris *et al*., (2018) that stated that freshwater ecosystems, due to the close connection to microplastics origins, have comparably, similar and/or higher microplastics quantities, and are common passageways of microplastics transfer into oceans (Dris *et al*., 2018). With respect to the Kenyan marine coastline, the higher proportions of fibers/filaments recovered in Lake Naivasha could be attributed to the concentration effect brought about by the relative small size of Lake Naivasha (Faure *et al*., 2015).
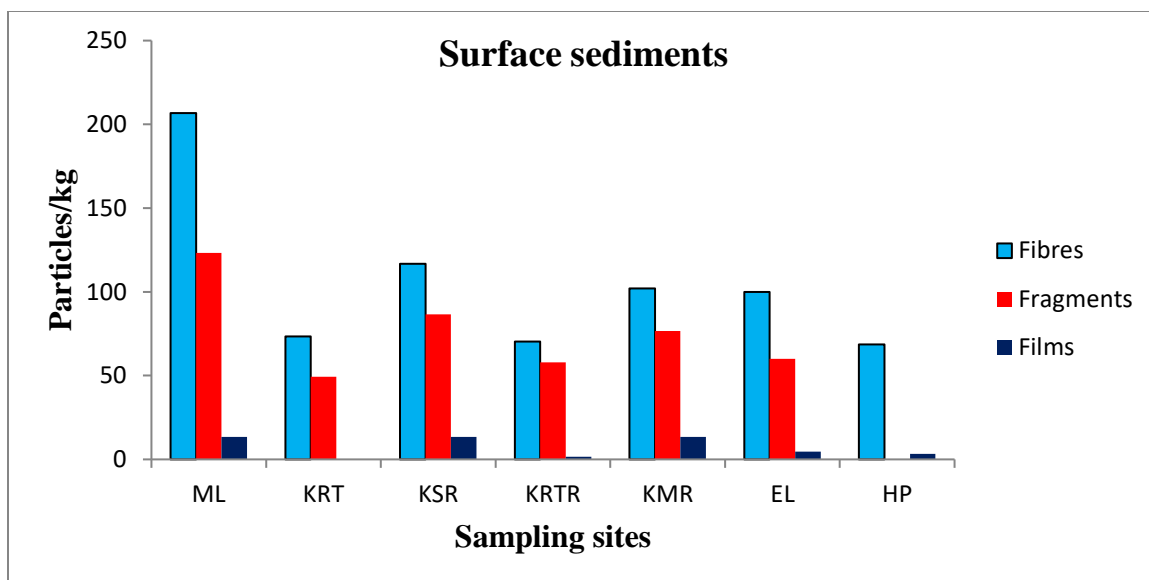
Figure 5: Proportions of shape categories of the microplastics recovered from surface sediments of Lake Naivasha.

ML- River Malewa mouth; KRT- Karati River mouth; KSR- Kasarani; KRTR- Sher Karuturi discharge outlet; KMR;Kamere beach; EL; Elsamere conservancy; HP- Hippo point.

Similarly in the surface sediments, fibers were present in all the samples (n=37) and exhibited a dominant abundance, accounting for 59.7% of all the recovered microplastics (Figure 5). Fragments (n=23) and films (n=2) were present in six out of the seven sampling sites each, with no pellets recovered in Lake Naivashas sediments. The substantial higher quantities of fragments can be attributed to the presence of denser microplastics in the sediments than in surface waters (Vaughan *et al*., 2017).

The high population growth rate around Lake Naivasha has been reported to increase pressure on the waste disposal systems causing a threat on the Lakes' health (Ndungu *et al*., 2015). This threat is compounded by the low degree of sewer treatment around the lake that only involves screening and organic matter decomposition. Screening aids in removal of large objects from the wastewater which is then aerated to enable the microbes oxygenate and decompose organic matter before being released into the environment (NAIVAWASS, 2019). Thus, the dominance of fibers and fragments and lack of primary pellets in Lake Naivasha could be an indication of household sewage effluent discharge into the lake and/or the breakdown of household plastic items, together

with a waste water treatment plant (WWTP) that is unable to capture microplastics (Hernandez *et al*., 2017).

Being secondary microplastics, fibers have been found to dominate sewage disposed sites, arising from laundry practices (machine washing of synthetic fabrics) and reaching concentrations of up to 100 fibers/L of effluent (Browne *et al*., 2011; Hernandez *et al*., 2017). They could be transported to the inflow rivers and consequently into the lake by run-off, occurring mostly during heavy rains. The fibrous microplastics dominance has also been attributed to the breakdown of fishing gear, plastic packaging materials and food service items (Andrady, 2011). The substantial proportion of blue, red and white/translucent particles (Figure 7) confirms this explanation as most discarded fishing nets and lines were determined to be made from these colored plastic fibers. Besides, white/transparent particles recovered in the urban lakes of China were reported to be attributed to the wide use of fishing lines and nets made from transparent plastic materials (Wang *et al.*, 2017). This study corroborates with similar studies in Bizerte lagoon of Northern Tunisia, Canadian Lake Ontario and River Thames basin in UK where fiber- and fragment-shaped particles were recovered as the dominant microplastics (Ballent *et al*., 2016; Horton *et al*., 2017; Toumi *et al*., 2019).

The microplastics were classified against their visual observed colors; black/brown, blue, red, green and white/translucent particles and graphically presented in Figure 6.
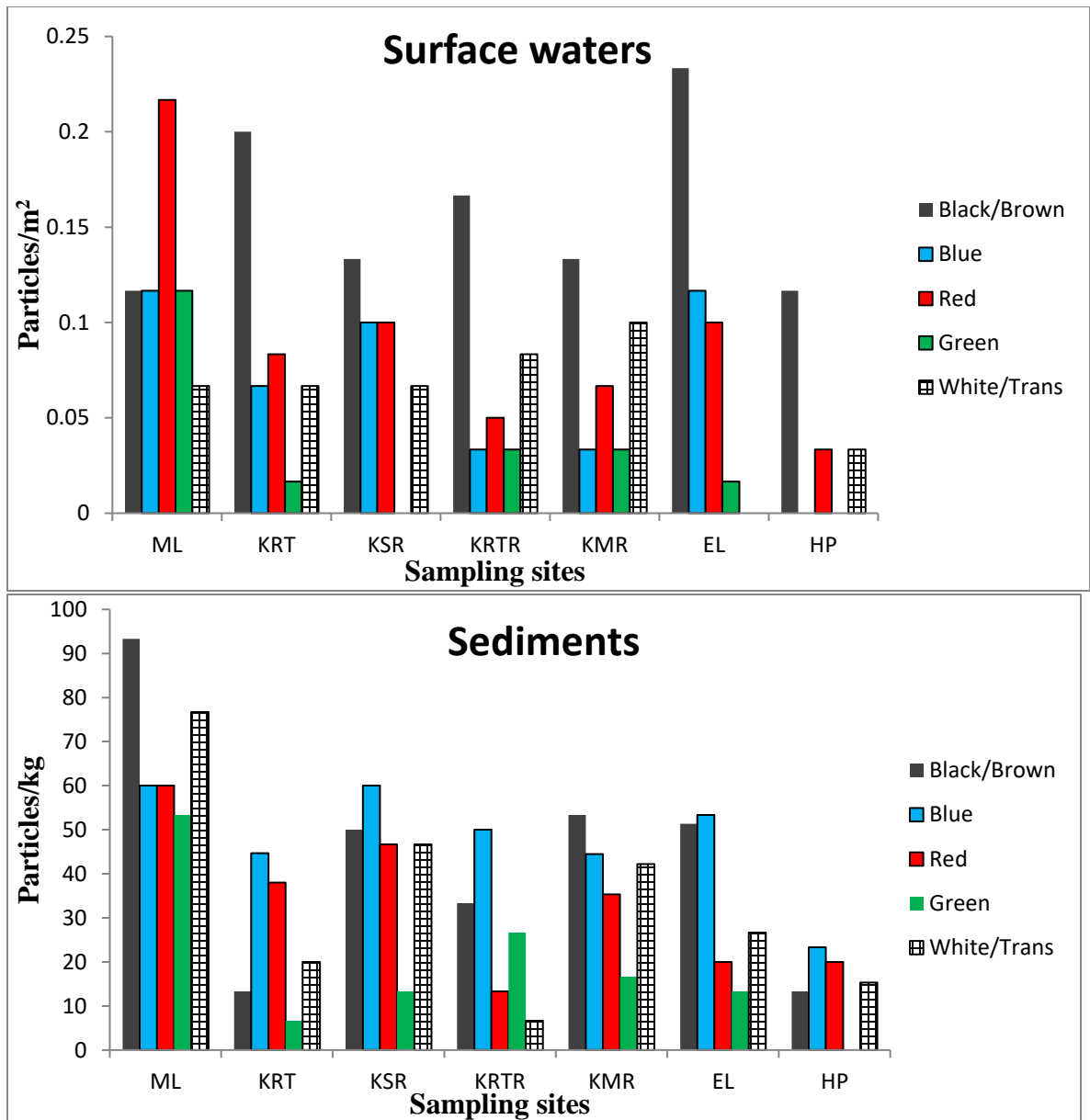
Figure 6: The color distribution of microplastics recovered from the different study sites of Lake Naivasha.

i- Surface waters and ii- surface sediments color distribution. ML- River Malewa mouth; KRT- Karati River mouth; KSR- Kasarani; KRTR- Sher Karuturi discharge outlet; KMR;Kamere beach; EL; Elsamere conservancy; HP- Hippo point.

Colored microplastics were dominant and accounted for approximately 81% and 85.5% of the recovered particles in Lake Naivasha surface waters and sediments respectively (Figure 6). Black/brown colored microplastics were dominant (39%) in Lake Naivashas' surface waters whereas in sediments, blue (27%) and black/brown (25%) microplastics

were dominant. White particles were not recovered in Elsamere Conservancy location surface waters, possibly due to the fact that human activities such as fishing, a major contributor of white particles (Wang *et al*., 2017), have been discouraged in this area. Since most plastic consumer goods are colored in view of improving their market appeal (Andrady and Neal, 2009), the observed dominance of colored microplastics is an indication that Lake Naivasha presumably derived these pollutants from the degradation of colored macro-plastic items. The dominating occurrence of colored microplastics triggers concerns on their effects to Lake Naivashas aquatic species. This is due to the veritable link that has been shown to exist between colored microplastics and their ingestion by aquatic species in both surface waters and sediments (Wright *et al*., 2013). For instance, studies have noted the presence of colored microplastics in several predatory fish, attributed to mistaken ingestion due to the microplastics resemblance with their zooplankton prey (Imhof *et al*., 2013; Sanchez *et al.*, 2014).

4.3.2 Microplastic chemical compositions

Polymer identification provides useful information on possible sources of plastic that have either weathered or disintegrated to yield microplastics. Proportions of the recovered microplastics were analyzed using Fourier transform infrared spectroscopy, according to (Hidalgo-Ruz *et al*., 2012). The spectrums yielded (Appendix 1) were correlated with standard spectra in the equipments database to obtain the microplastics polymer composition.

In surface waters, where a total of 86 particles were recovered, 23% were analyzed via FT-IR and yielded PE (n=4), PET (n=2), PES (n=7) and PP (n=5; Figure 7).
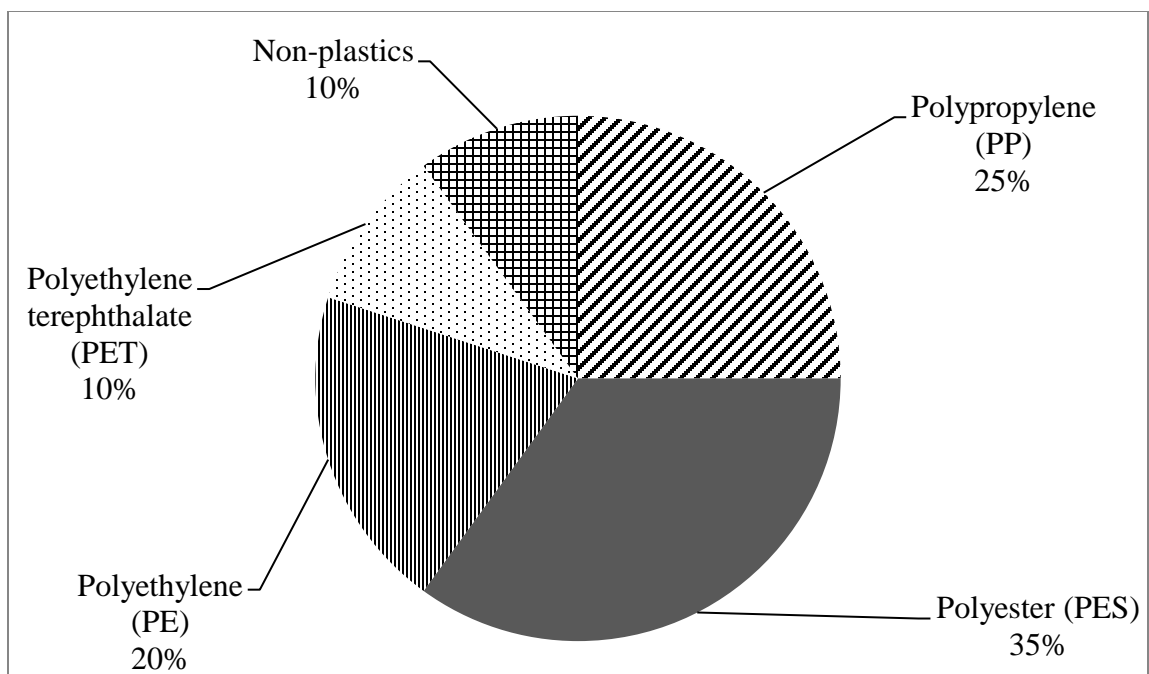
Figure 7: Percentage proportions of microplastic polymers recovered from Lake Naivasha surface waters. (n=20)

The high abundance of PE, PES and PP detected in the surface waters of Lake Naivasha corresponds with their huge production (accounting for more than 60% of plastics production) and usage in modern life ranging from plastic bags, bottles, containers to synthetic textiles (PlasticsEurope, 2016). Fishing activities in the lake could also have a significant contribution to the concentration of PE and PP polymers recovered as they are the main components of fishing nets and lines (Wang *et al*., 2018).

Similarly, fabric synthetic textiles which have become the current trend in the fashion industry, employ PET and PES in the production of clothes, fleeces and blankets, with an aim of designing cotton-like properties and ecofriendly products (Hernandez *et al*., 2017). Thus, the identification of PES (Figure 8) and fiber-like microplastic dominance suggests that laundry practices along the inflow rivers and around the lake is a major microplastic contributor. These are released by washing and have been shown to be a major contributor of microplastic fibers, discharged into the lake through household wastewater discharge, surface runoff and atmospheric deposition (Hernandez *et al*., 2017).

Similarly, in the surface sediments, 32% of the recovered 62 particles were analyzed to determine the polymer compositions. Lake Naivasha surface sediments yielded Polyethylene Nylon 2, PES, PP, Polyvinylchloride (PVC) and PET plastic polymers (Figure 8).
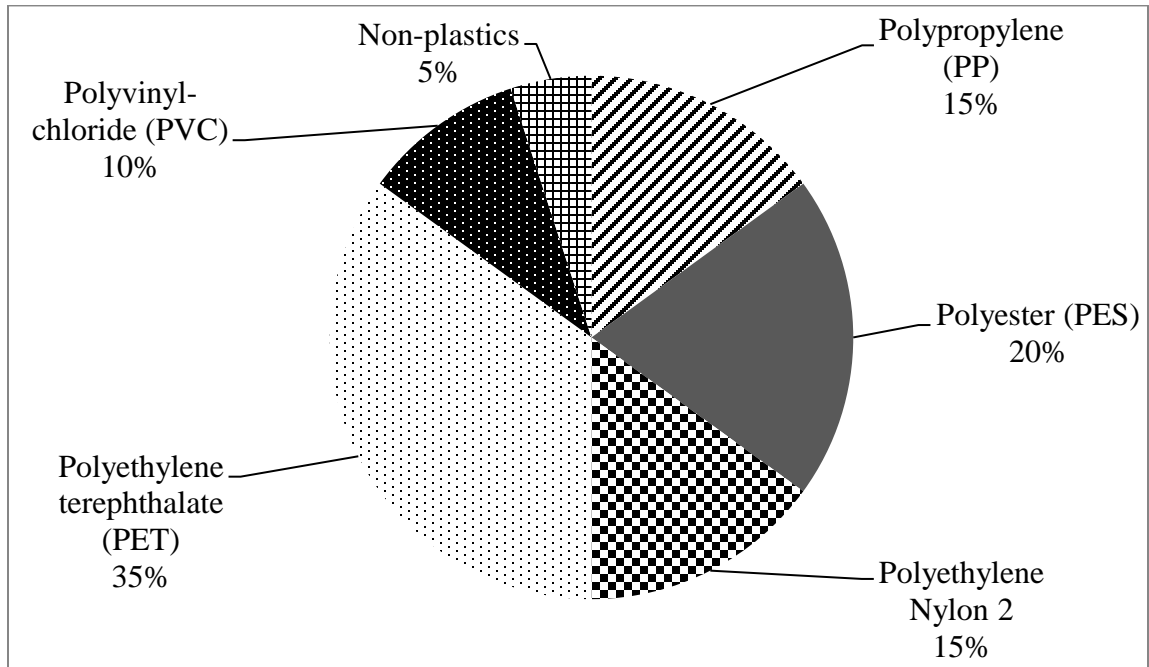

Figure 8: Percentage proportions of microplastic polymers recovered from Lake Naivasha surface sediments. (n=20)

The recovery of the dense (nylon, PET and PVC) microplastic polymers in the surface sediments was expected whereas the identification of PP and PES in sediments was interesting considering that the particles' density has been exclusively discussed to determine the microplastics position and transport routes in the water column. However, other factors like the particles' large surface-to-volume ratio, biofouling, and physical forces such as waves and tides may work together and alter the particles position in the water column (Zhao *et al.*, 2015). Fibers, mainly arising from synthetic textiles that are made of PES, have been reported to possess the largest surface area and are thus more susceptible to bio-foul and sink. The rate of biofouling varies depending on the nutrients availability, temperatures and/or the water turbulence (Vaughan *et al.*, 2017). Therefore, Lake Naivasha could experience high biofouling rates as a result of its shallowness and the high nutrients levels reported (section 4.2). A similar discussion would be used to

explain the recovery of PET (1.37g/cm^3), a dense than water polymer, from Lake Naivasha surface waters.

4.4 Correlational analysis

Besides providing data on microplastic abundance and composition in aquatic ecosystems, understanding the environmental variables that may potentially affect them is important. In this study, Pearson correlational analysis was done to obtain a preliminary insight of the interactions existing between various physical chemical parameters and microplastic abundance in surface waters and the results were tabulated in Table 5.

Table 5: Pearson correlation values for physical chemical parameters and microplastic abundance

Correlation values Physical- chemical parameter	r- value	p-value
Temperature	-0.1	0.65
pH	-0.2	0.4
Salinity	-	-
Turbidity	**0.79**	<0.0001*
Dissolved oxygen	-0.32	0.16
Conductivity	-0.48	0.028
Total dissolved solids	-0.022	0.92
Total nitrogen	**0.84**	<0.0001*
Total phosphorus	**0.79**	0.00014*

*- variables with significant correlational coefficients with microplastic abundance

Generally, the variables; salinity, pH, temp, DO, and TDS exhibited no statistical significant correlations with the microplastic abundance. On the other hand, strong positive correlations (highlighted in Table 5) were established between microplastic abundance and total nitrogen (r=0.84, p<0.0001), total phosphorus (r=0.79, p<0.0001) and turbidity (r=0.74, p=0.00014) as shown in the scatter plots in Figure 9. Further, a

weak negative correlation was exhibited between microplastic abundance and conductivity (r=-0.48, p=0.028) as shown in Appendix II.
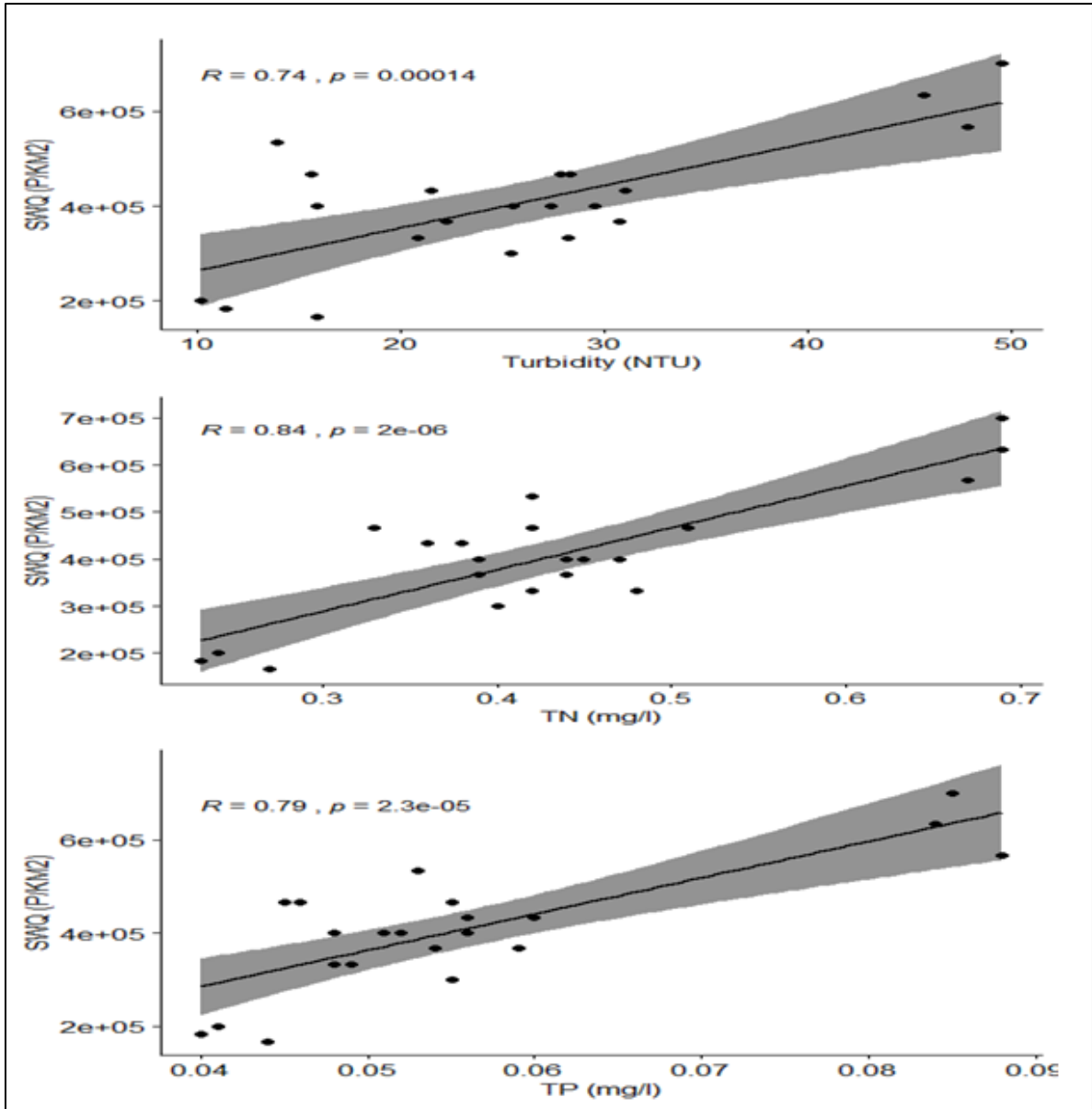

Figure 9: Pearson correlational scatter plots of microplastic association with environmental variables.

SWQ = surface water microplastic quantities measured per square km^2; TN= total nitrogen; TP = total phosphorus.

Therefore, as shown in the best fitting Pearson scatter plots in Figure 10, turbidity, total nitrogen, and total phosphorus had a significant relationship with the microplastic

abundance. These findings however should be taken in context that this correlational analysis aspect was only conducted in surface waters with respect to microplastic abundance of Lake Naivasha.

In a generalized additive model generated by La Daana *et al*., (2017), location, physicochemical parameters and atmospheric variables were shown to significantly affect the microplastic abundance. In China, a negative Pearson correlation was also established between microplastic abundance and the distance of 20 lakes from the corresponding urban centers (Wang *et al*., 2017).

In this study, the microplastic abundance and distribution in Lake Naivasha is shown to be associated by a combination of factors, such as location, the general water circulation, human activities in the catchment areas and around the lake, and certain physical chemical parameters (turbidity, total nitrogen and phosphorus). With increased settlements and urbanization around the lake and its catchments, large water abstractions for agriculture and domestic uses have increased pollution pressures, resulting in highly contaminated surface run-off from the catchment areas into the lake (Ndungu *et al*., 2015). Further, degradation in the catchment by activities such as forest clearance have culminated in increased soil erosion and consequent transport of nutrients into the lake (Njiru *et al*. 2017). This is attributed to the high volumes of pesticides and fertilizers used, together with other effluents from the horticultural farms and informal settlements around the lake, that have been reported to increase heavy metal and nutrients levels of the lake (Mutia *et al*., 2012), and consequently the microplastic quantities.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

1. In Lake Naivasha, the surface water physical-chemical parameters and nutrient concentrations were determined through field measurements in seven sampling locations. The variables (with range) ; temperature (21-26 ^{0}C), pH (7.25-7.92), turbidity (12-47 NTU), dissolved oxygen (6.7-9.0 mg/L), conductivity (0.26-0.278 mScm^{-1}), total dissolved solids (0.1786-0.1845 ppm), total nitrogen (0.25-0.68 mg/L) and phosphorus (0.042-0.086 mg/L) were found to record significant differences between the sampled locations of the lake. These were attributed to the presence of water hyacinth, water mass present and human activities, either along the main inflow rivers or around the lake. The high amounts of precipitation in the lakes catchment was also found to affect some water parameters such as pH and salinity, as a result of the dilution effect brought about by the high influx of freshwater. Similarly, although the nutrient levels were found to range below the WHO maximum permissible levels for lake water, the high concentrations recorded and mostly at the main intake river were attributed to the anthropogenic activities such as waste disposal, forest clearance and the intensive agricultural use of fertilizers and pesticide in the lakes catchments.

2. Microplastics were ubiquitously detected in all the samples from the seven sampled locations in both the surface waters and sediments of Lake Naivasha. Microplastic abundance averaged 0.407±0.135 particles/m^2 and 177.33±87.37 particles/kg in surface waters and sediments respectively. Highest microplastic concentrations in both the surface waters and sediments were recorded from the mouth of Lake Naivashas' major inflow river, the Malewa River. Similarly, the lowest microplastic quantities were recorded in Hippo Point, an area characterized by minimal anthropogenic disturbances. The microplastic levels recovered in Lake Naivasha surface waters and sediments suggests that the lake is greatly influenced by river-line influences and potential microplastic sources that include, but not limited to, ineffective industrial, household and municipal sewage

discharge into the lake together with land based pollution in River Malewa catchments.

3. Chemical characterization through FT-IR identified the recovered microplastics as PE, polyethylene nylon 2, PET, PES, PVC, and PP plastic polymers. PE, PES and PP were found to dominate surface waters whereas PET was dominant in the surface sediments. Similarly, colored ($\approx$83%) and fiber-shaped ($\approx$81%) microplastics were found to be dominant in both the surface waters and sediments. The chemical compositions of the microplastic particles recovered could be associated with a variety of plastic waste sources. Such included PP and PE used in the production of plastic bags, fishing line and nets, PES and PET used in the textile industries and the PET, Nylon and PVC used in food packaging containers and bottles. Moreover, the physical characteristics of the microplastics recovered were an indication that the lakes' microplastic pollution was resulted from secondary sources. The dominance of fragmented and colored microplastics serves as an indication that the lake suffers from pollution of secondary microplastics that result from the fragmentation of larger plastics in the adjacent terrestrial environments or in the lakes ecosystem. Thus, this concludes that Lake Naivashas' surface waters and sediments derive these pollutants from tourism, fishing, and other anthropogenic activities in/around the lake.

5.2 Recommendations

The findings reported in this study takes into account the field measurements collected in Lake Naivashas' surface waters in January, 2019. This study therefore recommends long term monitoring that would take into account more water quality parameters such as the organic pollutants and heavy metals that have been shown to associate with microplastics, and hence allow for the setting of management guidelines in the lake.

Secondly, the high concentrations of microplastics found in Lake Naivasha raises concern on the need to develop measures on prevention of release or input of plastics into aquatic ecosystems, as this could be the most effective way of minimizing plastic and microplastic pollution. This could be harnessed by improvement in plastic waste management along and around rivers and lakes, increased public awareness and

education to improve awareness of the general environment protection. Similarly, this could be achieved through the development and promotion of economic and environmental friendly plastic substitutes.

The high abundance and dominance of fibrous, fragmented and colored microplastics necessitates the implementation of measures to reduce household plastic-rich waste discharge into inflow rivers or/and the lake. The identification of microplastics sources in Lake Naivasha as household waste discharge, anthropogenic activities such as fishing and ineffective sewage treatment facilities necessitates the improvement of the sewage treatment infrastructure whereas developing suitable methods for the removal of microplastics from source points such as the household sinks and laundry outfalls.

Finally, this study only acts as a first step that identifies and evaluates the extent of microplastic pollution in the surface waters and sediments of Lake Naivasha, Kenya. The alarming levels detected surfaces the need to evaluate the accumulation and effects of microplastics to Lake Naivashas' aquatic organisms from the molecular to community levels, taking into account the associated influence of their ecosystem functions.

REFERENCES

Alencastro, D. (2012). Pollution due to plastics and microplastics in Lake Geneva and in the Mediterranean Sea. *Archives Des Sciences*, *65*, 157–164.

Anderson, D. M., Glibert, P. M., and Burkholder, J. M. (2002). Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. *Estuaries*, *25*(4), 704–726.

Andrady, A. L. (2011). Microplastics in the marine environment. *Marine Pollution Bulletin*, *62*(8), 1596–1605.

Andrady, A. L. (2017). The plastic in microplastics: a review. *Marine Pollution Bulletin*, *119*(1), 12–22.

Andrady, A. L., and Neal, M. A. (2009). Applications and societal benefits of plastics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 1977–1984.

Araújo, P. H. H., Sayer, C., Giudici, R., and Poco, J. G. R. (2002). Techniques for reducing residual monomer content in polymers: a review. *Polymer Engineering and Science*, *42*(7), 1442–1468.

Ashton, K., Holmes, L., and Turner, A. (2010). Association of metals with plastic production pellets in the marine environment. *Marine Pollution Bulletin*, *60*(11), 2050–2055.

Bakir, A., Rowland, S. J., and Thompson, R. C. (2014). Enhanced desorption of persistent organic pollutants from microplastics under simulated physiological conditions. *Environmental Pollution*, *185*, 16–23.

Ballent, A., Corcoran, P. L., Madden, O., Helm, P. A., and Longstaffe, F. J. (2016). Sources and sinks of microplastics in Canadian Lake Ontario nearshore, tributary and beach sediments. *Marine Pollution Bulletin*, *110*(1), 383–395.

Ballent, A., Purser, A., de Jesus Mendes, P., Pando, S., and Thomsen, L. (2012). Physical transport properties of marine microplastic pollution. *Biogeosciences Discussions*, *9*(12).

Biginagwa, F. J., Mayoma, B. S., Shashoua, Y., Syberg, K., and 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

Browne, M. A., Crump, P., Niven, S. J., Teuten, E., Tonkin, A., Galloway, T., and Thompson, R. (2011). Accumulation of microplastic on shorelines woldwide: sources and sinks. *Environmental Science and Technology*, *45*(21), 9175–9179.

Centers for Disease Control and Prevention. (2009). *Fourth National Report on Human Exposure to Environmental Chemicals*. *Environmental Health* (Vol. NCEH Pub.). Retrieved from http://www.cdc.gov/exposurereport/pdf/FourthReport.pdf

Clark, J. R., Cole, M., Lindeque, P. K., Fileman, E., Blackford, J., Lewis, C., and Galloway, T. S. (2016). Marine microplastic debris: a targeted plan for understanding and quantifying interactions with marine life. *Frontiers in Ecology and the Environment*, *14*(6), 317–324.

Cole, M., Webb, H., Lindeque, P. K., Fileman, E. S., Halsband, C., and Galloway, T. S. (2014). Isolation of microplastics in biota-rich seawater samples and marine organisms. *Scientific Reports*, *4*, 4528.

Dris, R., Gasperi, J., Rocher, V., Saad, M., Renault, N., and Tassin, B. (2015). Microplastic contamination in an urban area: a case study in Greater Paris. *Environmental Chemistry*, *12*(5), 592–599.

Dris, R., Imhof, H. K., Löder, M. G. J., Gasperi, J., Laforsch, C., and Tassin, B. (2018). Microplastic contamination in freshwater systems: Methodological challenges, occurrence and sources. In *Microplastic Contamination in Aquatic Environments* (pp. 51–93). Elsevier.

Duis, K., and Coors, A. (2016). Microplastics in the aquatic and terrestrial environment: sources (with a specific focus on personal care products), fate and effects. *Environmental Sciences Europe*, *28*(1), 2.

Eerkes-Medrano, D., Thompson, R. C., and Aldridge, D. C. (2015). Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. *Water Research*, *75*, 63–82.

Eriksen, M., Mason, S., Wilson, S., Box, C., Zellers, A., Edwards, W., and Amato, S. (2013). Microplastic pollution in the surface waters of the Laurentian Great Lakes. *Marine Pollution Bulletin*, *77*(1–2), 177–182.

Ernst, T., Popp, R., and van Eldik, R. (2000). Quantification of heavy metals for the recycling of waste plastics from electrotechnical applications. *Talanta*, *53*(2), 347–357.

Everard, M., Vale, J. A., Harper, D. M., and Tarras-Wahlberg, H. (2002). The physical attributes of the Lake Naivasha catchment rivers. In *Lake Naivasha, Kenya* (pp. 13–25). Springer.

Fageria, N. K. (2016). *The use of nutrients in crop plants*. CRC press.

Faure, F., Demars, C., Wieser, O., Kunz, M., and De Alencastro, L. F. (2015). Plastic pollution in Swiss surface waters: nature and concentrations, interaction with pollutants. *Environmental Chemistry*, *12*(5), 582–591.

Fendall, L. S., and Sewell, M. A. (2009). Contributing to marine pollution by washing your face: microplastics in facial cleansers. *Marine Pollution Bulletin*, *58*(8), 1225–1228.

Fischer, E. K., Paglialonga, L., Czech, E., and Tamminga, M. (2016). Microplastic pollution in lakes and lake shoreline sediments–A case study on Lake Bolsena and Lake Chiusi (central Italy). *Environmental Pollution*, *213*, 648–657.

Free, C. M., Jensen, O. P., Mason, S. A., Eriksen, M., Williamson, N. J., and Boldgiv, B. (2014). High-levels of microplastic pollution in a large, remote, mountain lake. *Marine Pollution Bulletin*, *85*(1), 156–163.

Frère, L., Paul-Pont, I., Rinnert, E., Petton, S., Jaffré, J., Bihannic, I., and Huvet, A. (2017). Influence of environmental and anthropogenic factors on the composition, concentration and spatial distribution of microplastics: a case study of the Bay of Brest (Brittany, France). *Environmental Pollution*, *225*, 211–222.

Frias, J., and Nash, R. (2019). Microplastics: Finding a consensus on the definition. *Marine Pollution Bulletin*, *138*, 145–147.

Frias, J., Otero, V., and Sobral, P. (2014). Evidence of microplastics in samples of zooplankton from Portuguese coastal waters. *Marine Environmental Research*, *95*, 89–95.

GESAMP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection. (2015). Sources, fate and effects of microplastics in the marine environment: a global assessment". *Reports and Studies GESAMP*, *90*(April), 96.

Geyer, R., Jambeck, J. R., and Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances*, *3*(7), e1700782.

Government of Kenya. (2010). Cancer Burden in the Country. Retrieved May 29, 2018, from https://kenyacancernetwork.wordpress.com/kenya-cancer-facts

Green belt Movement. (2014). The Green Belt Movement. Retrieved May 30, 2018, from www.greenbeltmovement.org/node/772

Hernandez, E., Nowack, B., and Mitrano, D. M. (2017). Polyester textiles as a source of microplastics from households: a mechanistic study to understand microfiber release during washing. *Environmental Science and Technology*, *51*(12), 7036–7046.

Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., and Thiel, M. (2012). Microplastics in the marine environment: a review of the methods used for identification and quantification. *Environmental Science and Technology*, *46*(6), 3060–3075.

Hoellein, T. J., McCormick, A., and Kelly, J. J. (2014). Riverine microplastic: abundance and bacterial community colonization. In *Abstract. Joint Aquatic Sciences Meeting. Portland*.

Holmes, L. A., Turner, A., and Thompson, R. C. (2014). Interactions between trace metals and plastic production pellets under estuarine conditions. *Marine Chemistry*, *167*, 25–32.

Horton, A. A., Svendsen, C., Williams, R. J., Spurgeon, D. J., and Lahive, E. (2017). Large microplastic particles in sediments of tributaries of the River Thames, UK–Abundance, sources and methods for effective quantification. *Marine Pollution Bulletin*, *114*(1), 218–226.

Imhof, H. K., Ivleva, N. P., Schmid, J., Niessner, R., and Laforsch, C. (2013). Contamination of beach sediments of a subalpine lake with microplastic particles. *Current Biology*, *23*(19), R867–R868.

Jiang, P., Zhao, S., Zhu, L., and Li, D. (2018). Microplastic-associated bacterial assemblages in the intertidal zone of the Yangtze Estuary. *Science of the Total Environment*, *624*, 48–54.

Kamau, J. N., Gachanja, A., Ngila, C., Kazungu, J. M., and Zhai, M. (2008). Anthropogenic and seasonal influences on the dynamics of selected heavy metals in Lake Naivasha, Kenya. *Lakes and Reservoirs: Research and Management*, *13*(2), 145–154.

Klein, S., Worch, E., and Knepper, T. P. (2015). Occurrence and spatial distribution of microplastics in river shore sediments of the Rhine-Main area in Germany. *Environmental Science and Technology*, *49*(10), 6070–6076.

Koelmans, A. A., Besseling, E., Wegner, A., and Foekema, E. M. (2013). Plastic as a carrier of POPs to aquatic organisms: a model analysis. *Environmental Science and Technology*, *47*(14), 7812–7820.

Koelmans, A. A., Besseling, E., and Foekema, E. M. (2014). Leaching of plastic additives to marine organisms. *Environmental Pollution*, *187*, 49-54.

Kosore, C., Ojwang, L., Maghanga, J., Kamau, J., Kimeli, A., Omukoto, J., and Magori, C. (2018). Occurrence and ingestion of microplastics by zooplankton in Kenya's marine environment: first documented evidence. *African Journal of Marine Science*, *40*(3), 225–234.

La Daana, K. K., Officer, R., Lyashevska, O., Thompson, R. C., and O'Connor, I. (2017). Microplastic abundance, distribution and composition along a latitudinal gradient in the Atlantic Ocean. *Marine Pollution Bulletin*, *115*(1–2), 307–314.

Law, K. L., and Thompson, R. C. (2014). Microplastics in the seas. *Marine Pollution Bulletin*, *144*.

Li, J., Liu, H., and Chen, J. P. (2018). Microplastics in freshwater systems: A review on occurrence, environmental effects, and methods for microplastics detection. *Water Research*, *137*, 362–374.

Lima, A. R. A., Barletta, M., and Costa, M. F. (2015). Seasonal distribution and interactions between plankton and microplastics in a tropical estuary. *Estuarine, Coastal and Shelf Science*, *165*, 213–225.

Lima, A. R. A., Costa, M. F., and Barletta, M. (2014). Distribution patterns of microplastics within the plankton of a tropical estuary. *Environmental Research*, *132*, 146–155.

Lots, F. A. E., Behrens, P., Vijver, M. G., Horton, A. A., and Bosker, T. (2017). A large-scale investigation of microplastic contamination: Abundance and characteristics of microplastics in European beach sediment. *Marine Pollution Bulletin*, *123*(1–2), 219–226.

Maes, T., Van der Meulen, M. D., Devriese, L. I., Leslie, H. A., Huvet, A., Frère, L., Vethaak, A. D. (2017). Microplastics baseline surveys at the water surface and in sediments of the North-East Atlantic. *Frontiers in Marine Science*, *4*, 135.

Masura, J., Baker, J. E., Foster, G. D., Arthur, C., and Herring, C. (2015). Laboratory methods for the analysis of microplastics in the marine environment: recommendations for quantifying synthetic particles in waters and sediments. *NOAA Technical Memorandum*.

Mato, Y., Isobe, T., Takada, H., Kanehiro, H., Ohtake, C., and Kaminuma, T. (2001). Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. *Environmental Science and Technology*, *35*(2), 318–324.

Mironga, J. M., Mathooko, J. M., and Onywere, S. M. (2012). Effect of water hyacinth infestation on the physicochemical characteristics of Lake Naivasha.

Musyoka, S. M. (2017). *Phytoplankton composition, growth rates and oil production potential of fast growing species from Lake Naivasha and water reservoirs at Embu University College, M.Sc Thesis, University of Embu, Kenya*.

Mutia, T. M., Virani, M. Z., Moturi, W. N., Muyela, B., Mavura, W. J., and Lalah, J. O. (2012). Copper, lead and cadmium concentrations in surface water, sediment and fish, C. Carpio, samples from Lake Naivasha: effect of recent anthropogenic activities. *Environmental Earth Sciences*, *67*(4), 1121–1130.

Mutungwa, D. M. (2011). *Effects of climate change and human activity on lake levels in the Kenyan rift (case study Naivasha)*.

Naidoo, T., Glassom, D., and Smit, A. J. (2015). Plastic pollution in five urban estuaries of KwaZulu-Natal, South Africa. *Marine Pollution Bulletin*, *101*(1), 473–480.

NAIVAWASS. (2019). Naivasha Water and Sanitation Company Ltd | SANITATION SERVICES - Naivasha Water and Sanitation Company Ltd. Retrieved October 24, 2019, from https://www.naivashawater.co.ke/sewer

Ndungu, J., Augustijn, D. C. M., Hulscher, S. J. M. H., Fulanda, B., Kitaka, N., and Mathooko, J. M. (2015). A multivariate analysis of water quality in Lake Naivasha, Kenya. *Marine and Freshwater Research*, *66*(2), 177–186.

Nel, H. A., and Froneman, P. W. (2015). A quantitative analysis of microplastic pollution along the south-eastern coastline of South Africa. *Marine Pollution Bulletin*, *101*(1), 274–279.

Njiru, J., Morara, G., Waithaka, E., and Mugo, J. (2015). Fish kills in lake Naivasha, Kenya: What was the probable cause. *International Journal of Fisheries and Aquatic Studies*, *3*(1), 179–184.

Njiru, J., Waithaka, E., and Aloo, P. A. (2017). An Overview of the Current Status of Lake Naivasha Fishery : Challenges and Management Strategies, 1–11. https://doi.org/10.2174/1874401X01710010001

Ochieng, E. Z., Lalah, J. O., and Wandiga, S. O. (2007). Analysis of heavy metals in water and surface sediment in five rift valley lakes in Kenya for assessment of recent increase in anthropogenic activities. *Bulletin of Environmental Contamination and Toxicology*, *79*(5), 570–576.

Ogendi, G. M., Maina, G. M., Mbuthia, J. W., Koech, H. K., Ratemo, C. M., and Koskey, J. C. (2014). Heavy metal concentrations in water, sediments and common carp (Cyprinus carpio) fish species from Lake Naivasha, Kenya. *Research Journal of Environmental and Earth Sciences*, *6*(8), 416–423.

Oguge, N. O. (2019). Circular Economy Measures: An Opportunity For Rethinking Plastics Waste Governance in Kenya. *Law Env't & Dev. J.*, *15*, 124.

Omondi, D. O., Wairimu, M. A., Aketch, W. L., William, S. A., Trick, C. G., and Creed, I. F. (2015). Faecal pollution and solar purification of community water sources within Lake Naivasha basin, Kenya. *Journal of Water Sanitation and Hygiene for Development*, *5*(2), 252–260.

Peixoto, D., Pinheiro, C., Amorim, J., Oliva-Teles, L., Guilhermino, L., and Vieira, M. N. (2019). Microplastic pollution in commercial salt for human consumption: A review. *Estuarine, Coastal and Shelf Science*.

Peng, G., Xu, P., Zhu, B., Bai, M., and Li, D. (2018). Microplastics in freshwater river sediments in Shanghai, China: A case study of risk assessment in mega-cities. *Environmental Pollution*, *234*, 448–456.

Pivokonsky, M., Cermakova, L., Novotna, K., Peer, P., Cajthaml, T., and Janda, V. (2018). Occurrence of microplastics in raw and treated drinking water. *Science of The Total Environment*, *643*, 1644–1651.

PlasticsEurope, E. (2016). Plastics—the facts 2016. An analysis of European plastics production, demand and waste data.

Qiu, Q., Peng, J., Yu, X., Chen, F., Wang, J., and Dong, F. (2015). Occurrence of microplastics in the coastal marine environment: first observation on sediment of China. *Marine Pollution Bulletin*, *98*(1–2), 274–280.

Qiu, Q., Tan, Z., Wang, J., Peng, J., Li, M., and Zhan, Z. (2016). Extraction, enumeration and identification methods for monitoring microplastics in the environment. *Estuarine, Coastal and Shelf Science*, *176*, 102–109.

Rochman, C. M., Hoh, E., Kurobe, T., and Teh, S. J. (2013). Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Scientific Reports*, *3*, 3263.

Sanchez, W., Bender, C., and Porcher, J.-M. (2014). Wild gudgeons (Gobio gobio) from French rivers are contaminated by microplastics: preliminary study and first evidence. *Environmental Research*, *128*, 98–100.

SAPEA. (2019). *Science Advice for Policy by European Academies - A Scientific Perspective on Microplastics in Nature and Society*. Berlin.

Scherer, C., Weber, A., Lambert, S., and Wagner, M. (2018). Interactions of microplastics with freshwater biota. In *Freshwater Microplastics* (pp. 153–180). Springer.

Schoumans, O. F., Chardon, W. J., Bechmann, M. E., Gascuel-Odoux, C., Hofman, G., Kronvang, B., Dorioz, J.-M. (2014). Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: a review. *Science of the Total Environment*, *468*, 1255–1266.

Smith, B. C. (2011). *Fundamentals of Fourier transform infrared spectroscopy*. CRC press.

Song, Y. K., Hong, S. H., Jang, M., Han, G. M., Rani, M., Lee, J., and Shim, W. J. (2015). A comparison of microscopic and spectroscopic identification methods for analysis of microplastics in environmental samples. *Marine Pollution Bulletin*, *93*(1–2), 202–209.

Song, Y. K., Hong, S. H., Jang, M., Kang, J.-H., Kwon, O. Y., Han, G. M., and Shim, W. J. (2014). Large accumulation of micro-sized synthetic polymer particles in the sea surface microlayer. *Environmental Science and Technology*, *48*(16), 9014–9021.

Stoof-Leichsenring, K. R., Junginger, A., Olaka, L. A., Tiedemann, R., and Trauth, M. H. (2011). Environmental variability in Lake Naivasha, Kenya, over the last two centuries. *Journal of Paleolimnology*, *45*(3), 353–367.

Su, L., Xue, Y., Li, L., Yang, D., Kolandhasamy, P., Li, D., and Shi, H. (2016). Microplastics in taihu lake, China. *Environmental Pollution*, *216*, 711–719.

Sutherland, W. J., Bardsley, S., Bennun, L., Clout, M., Côté, I. M., Depledge, M. H., … Watkinson, A. R. (2011). Horizon scan of global conservation issues for 2011. *Trends in Ecology and Evolution*, *26*(1), 10–16.

Tagg, A. S., Sapp, M., Harrison, J. P., and Ojeda, J. J. (2015). Identification and quantification of microplastics in wastewater using focal plane array-based reflectance micro-FT-IR imaging. *Analytical Chemistry*, *87*(12), 6032–6040.

Talsness, C. E., Andrade, A. J. M., Kuriyama, S. N., Taylor, J. A., and Vom Saal, F. S. (2009). Components of plastic: experimental studies in animals and relevance for human health. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 2079–2096.

Thiel, M., and Gutow, L. (2005). The ecology of rafting in the marine environment. II. The rafting organisms and community. In *Oceanography and Marine Biology* (pp. 289–428). CRC Press.

Toumi, H., Abidli, S., and Bejaoui, M. (2019). Microplastics in freshwater environment: the first evaluation in sediments from seven water streams surrounding the lagoon of Bizerte (Northern Tunisia). *Environmental Science and Pollution Research*, 1–10.

Tsang, Y. Y., Mak, C. W., Liebich, C., Lam, S. W., Sze, E. T. P., and Chan, K. M. (2017). Microplastic pollution in the marine waters and sediments of Hong Kong. *Marine Pollution Bulletin*, *115*(1–2), 20–28.

Turra, A., Manzano, A. B., Dias, R. J. S., Mahiques, M. M., Barbosa, L., Balthazar-Silva, D., and Moreira, F. T. (2014). Three-dimensional distribution of plastic pellets in sandy beaches: shifting paradigms. *Scientific Reports*, *4*, 4435.

Van Cauwenberghe, L., Claessens, M., Vandegehuchte, M. B., Mees, J., and Janssen, C. R. (2013). Assessment of marine debris on the Belgian Continental Shelf. *Marine Pollution Bulletin*, *73*(1), 161–169.

Van Cauwenberghe, L., Devriese, L., Galgani, F., Robbens, J., and Janssen, C. R. (2015). Microplastics in sediments: a review of techniques, occurrence and effects. *Marine Environmental Research*, *111*, 5–17.

Vandermeersch, G., Van Cauwenberghe, L., Janssen, C. R., Marques, A., Granby, K., Fait, G., and Robbens, J. (2015). A critical view on microplastic quantification in aquatic organisms. *Environmental Research*, *143*, 46–55.

Vaughan, R., Turner, S. D., and Rose, N. L. (2017). Microplastics in the sediments of a UK urban lake. *Environmental Pollution*, *229*, 10–18.

Vianello, A., Boldrin, A., Guerriero, P., Moschino, V., Rella, R., Sturaro, A., and Da Ros, L. (2013). Microplastic particles in sediments of Lagoon of Venice, Italy: First observations on occurrence, spatial patterns and identification. *Estuarine, Coastal and Shelf Science*, *130*, 54–61.

Wagner, M., Scherer, C., Alvarez-Muñoz, D., Brennholt, N., Bourrain, X., Buchinger, S., Marti, T. (2014). Microplastics in freshwater ecosystems: what we know and what we need to know. *Environmental Sciences Europe*, *26*(1), 12.

Wang, W., Ndungu, A. W., Li, Z., and Wang, J. (2017). Microplastics pollution in inland freshwaters of China: a case study in urban surface waters of Wuhan, China. *Science of the Total Environment*, *575*, 1369–1374.

Wang, W., Yuan, W., Chen, Y., and Wang, J. (2018). Microplastics in surface waters of dongting lake and hong lake, China. *Science of the Total Environment*, *633*, 539–545.

Wright, S. L., Thompson, R. C., and Galloway, T. S. (2013). The physical impacts of microplastics on marine organisms: a review. *Environmental Pollution*, *178*, 483–492.

Yan, Z., Han, W., Peñuelas, J., Sardans, J., Elser, J. J., Du, E., and Fang, J. (2016). Phosphorus accumulates faster than nitrogen globally in freshwater ecosystems under anthropogenic impacts. *Ecology Letters*, *19*(10), 1237–1246.

Yang, D., Shi, H., Li, L., Li, J., Jabeen, K., and Kolandhasamy, P. (2015). Microplastic pollution in table salts from China. *Environmental Science and Technology*, *49*(22), 13622–13627.

Yokota, K., Waterfield, H., Hastings, C., Davidson, E., Kwietniewski, E., and Wells, B. (2017). Finding the missing piece of the aquatic plastic pollution puzzle: Interaction between primary producers and microplastics. *Limnology and Oceanography Letters*, *2*(4), 91–104.

Zbyszewski, M., and Corcoran, P. L. (2011). Distribution and degradation of fresh water plastic particles along the beaches of Lake Huron, Canada. *Water, Air, and Soil Pollution*, *220*(1–4), 365–372.

Zbyszewski, M., Corcoran, P. L., and Hockin, A. (2014). Comparison of the distribution and degradation of plastic debris along shorelines of the Great Lakes, North America. *Journal of Great Lakes Research*, *40*(2), 288–299.

Zhao, S., Zhu, L., and Li, D. (2015). Microplastic in three urban estuaries, China. *Environmental Pollution*, *206*, 597–604.

Zhao, S., Zhu, L., and Li, D. (2016). Microscopic anthropogenic litter in terrestrial birds from Shanghai, China: not only plastics but also natural fibers. *Science of the Total Environment*, *550*, 1110–1115.
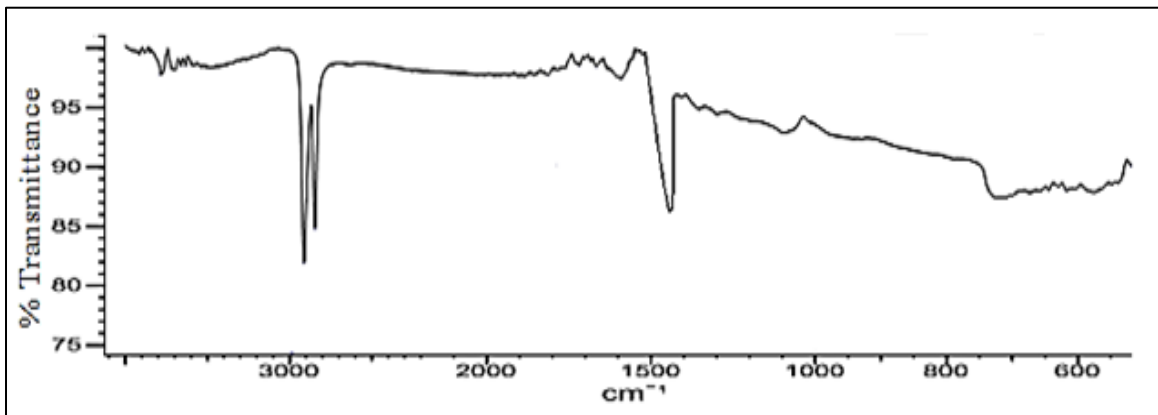
APPENDICES

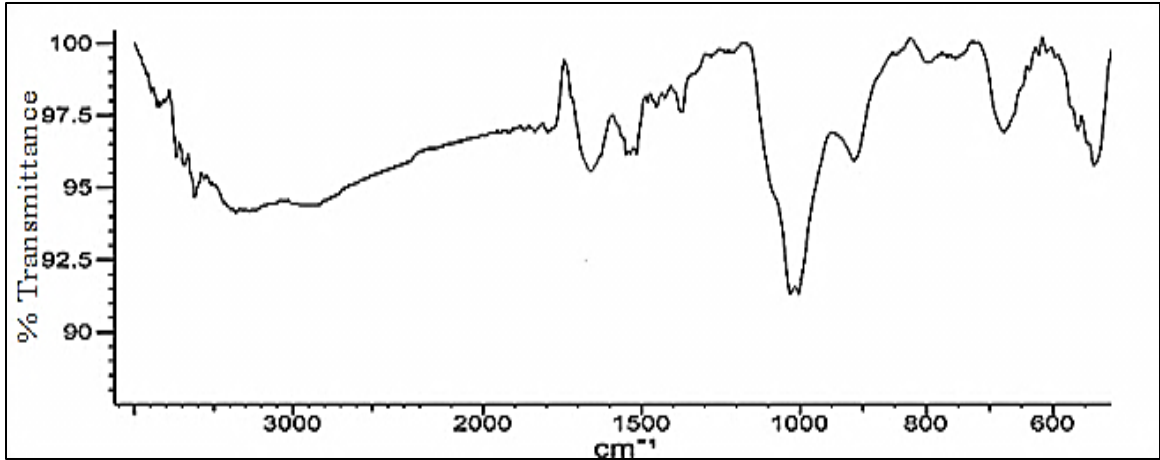**Appendix 1: Spectra yielded from FT-IR for microplastics chemical characterization**
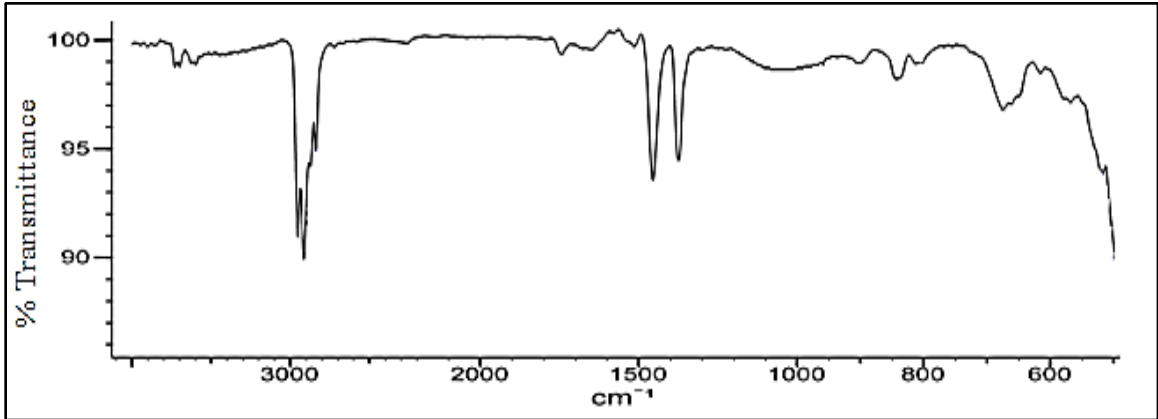
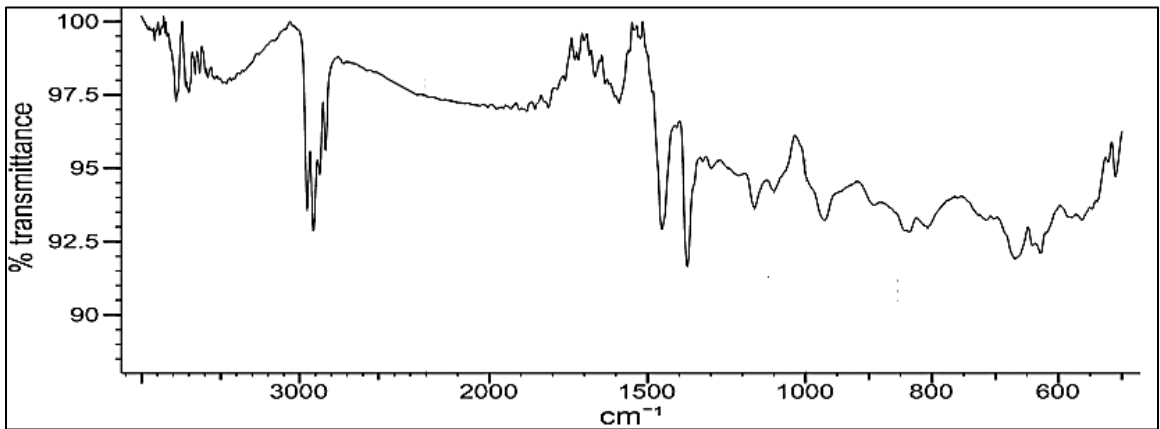Spectral match; Polyethylene (0.83)
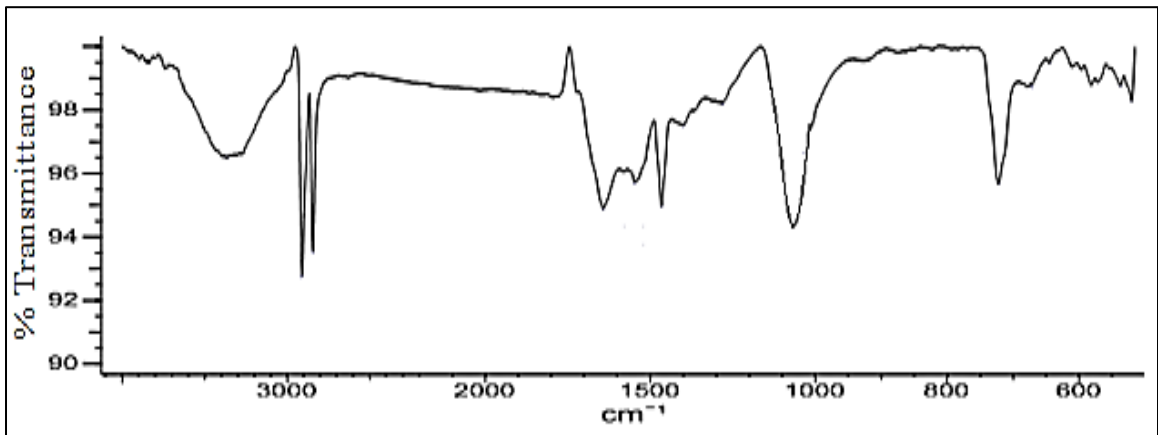
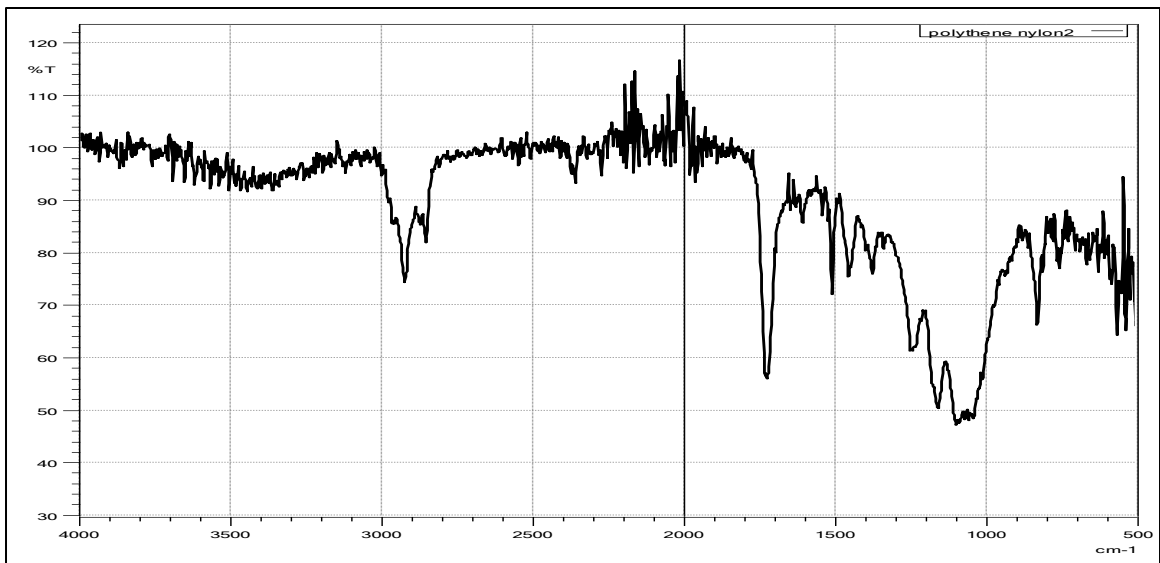Spectral match; Polyester (0.86)

Spectral match; Polypropylene (0.87)
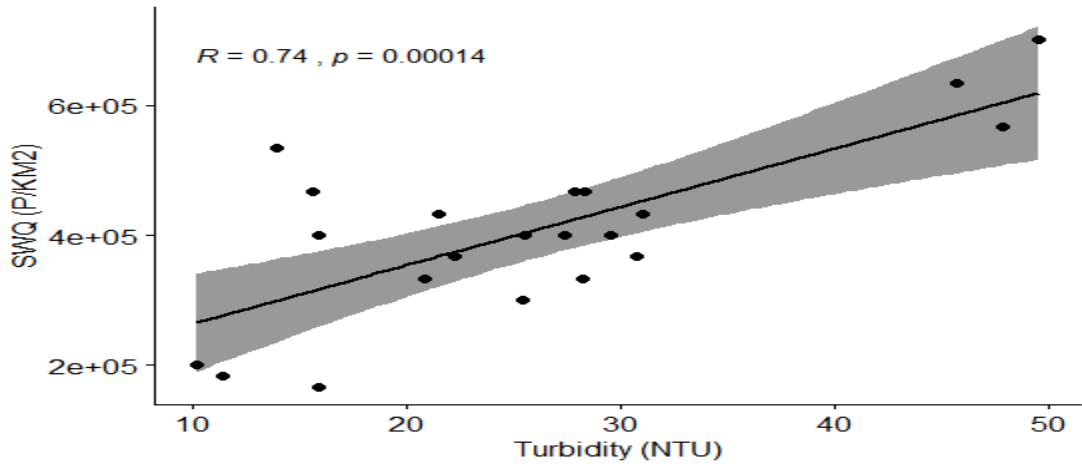
Spectral match; Polyester (0.77)
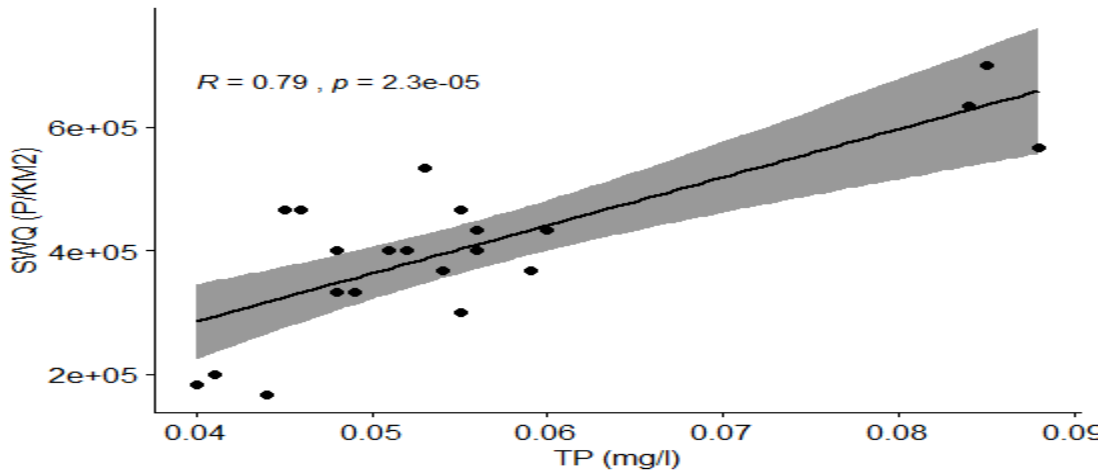

Spectral match; Polyvinylchloride (0.72)
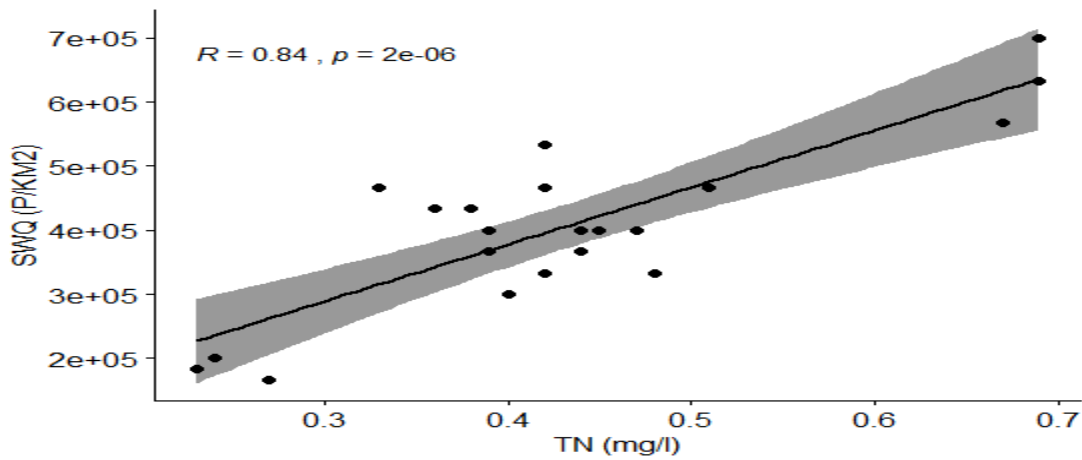

Spectral match; Polyethylene nylon 2 (0.77)

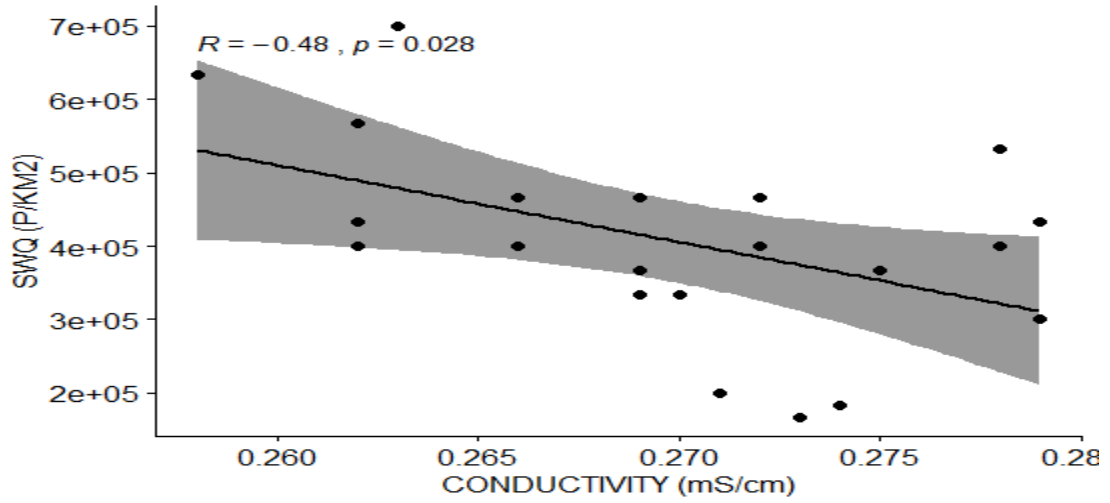**Appendix II: Pearson correlation scatter plots of the studied physical-chemical parameters and the microplastic abundance in Lake Naivasha**

Microplastic quantities vs. Turbidity

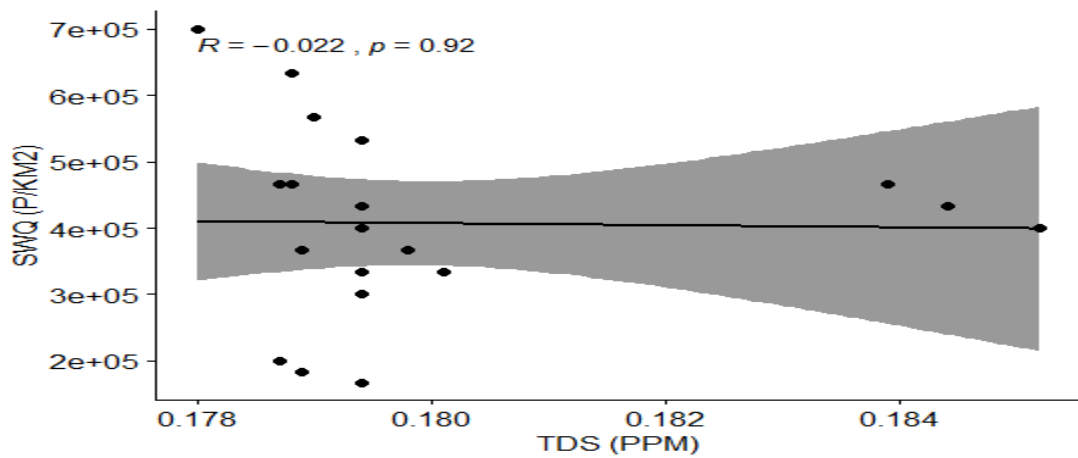

Microplastic quantities vs. Total Phosphorus (TP)
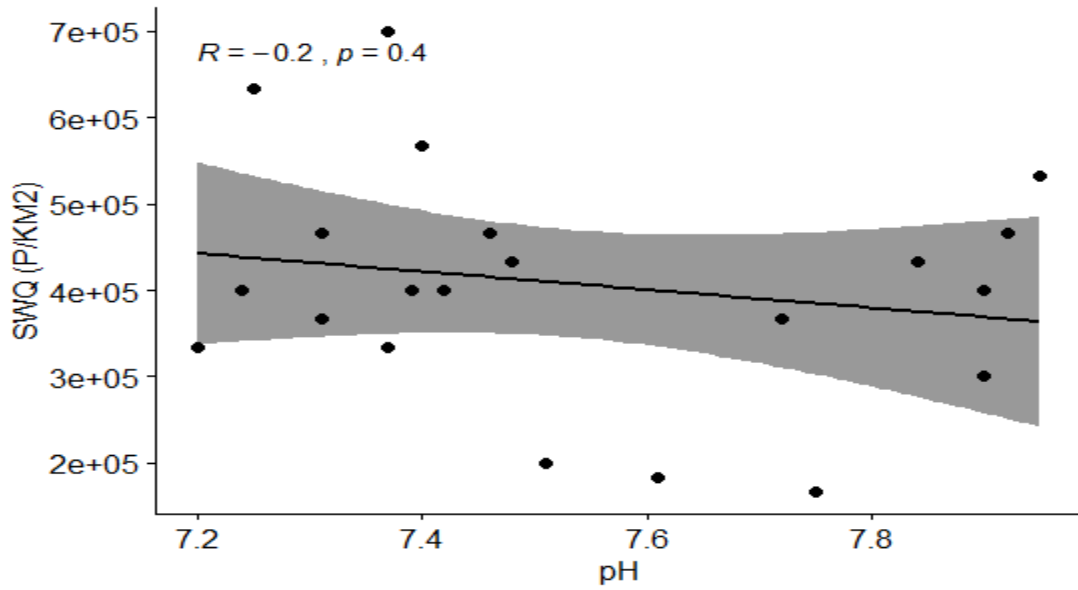

Microplastic quantities vs. Total Nitrogen (TN)
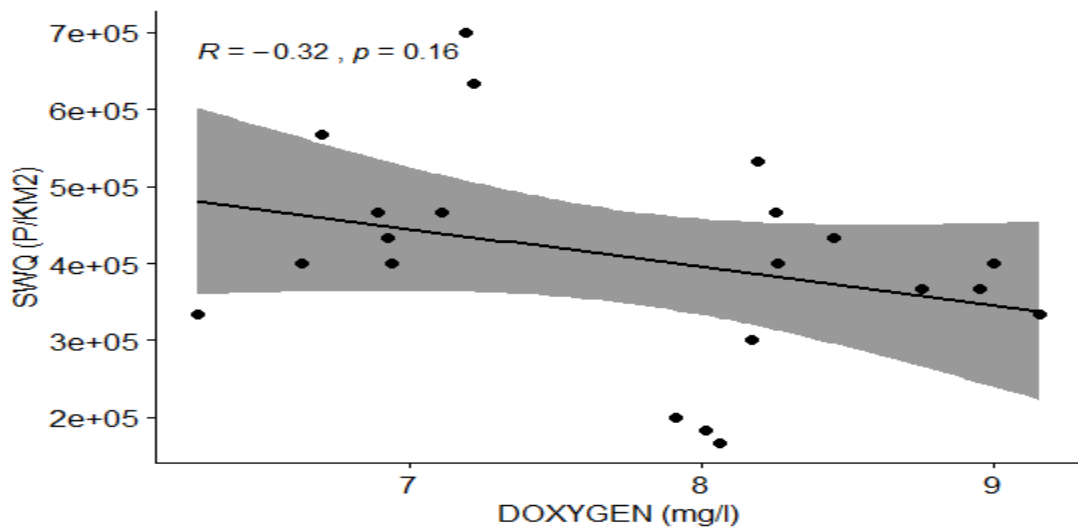
Microplastic quantities vs. Conductivity
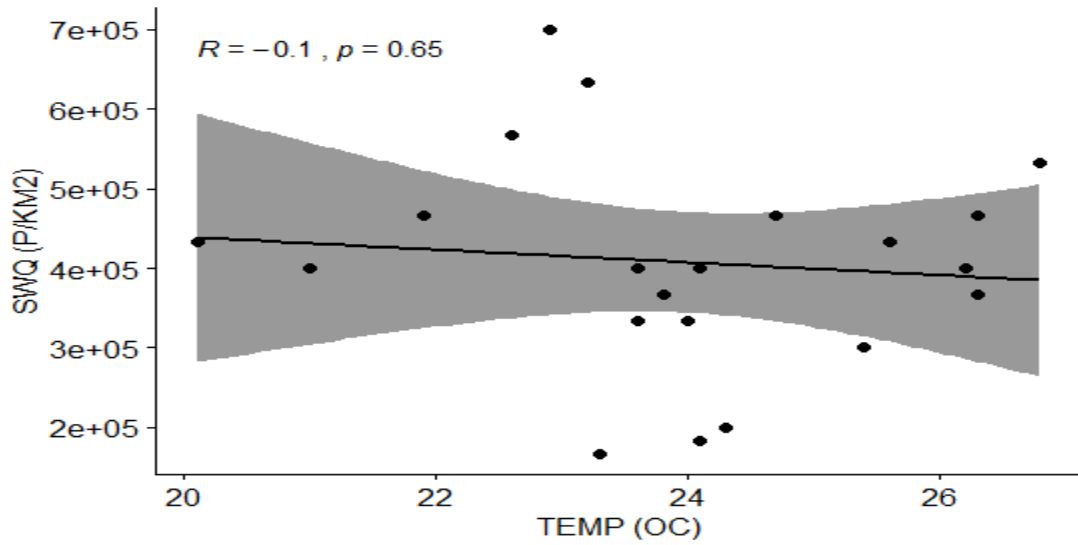
Microplastic quantities vs. Temperature

Microplastic quantities vs. Total Dissolved Solids

Microplastic quantities vs. pH

Microplastic quantities vs. Dissolved Oxygen